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THESIS

PARAMETRIC ANALYSIS OF COMBUSTION
OF POROUS MEDIUM

Antonio Carlos de Souza Serapiao

December 1985

Thesis Advisor: David Salinas

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Parametric Analysis of Combustion of Porous Medium

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

A computer program for a transient one-dimensional mathematical model of combustion in porous medium was used to investigate the effects of several parameters on system behavior . Results show the effects of medium thickness , permeability and reaction order on combustion . In addition, the effect of heat input on combustion was also studied .

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I. INTRODUCTION

The goal of this thesis is to study the combustion behavior of porous graphite . The mathematical model developed by VATIKIOTIS (1) is a transient, one-dimensional model of a porous medium consisting of spherical particles , or cylindrical fibers of graphite .

The model covers several aspects : mass transfer, heat transfer, combustion , airflow , and temperature dependency of thermophysical properties. Geometric parameters of the porous medium include porosity (p) and medium thickness (L). The porous medium has interconnected pores which permit air flow through the medium. This air flow was modeled by the continuity equation and Darcy's Law . The porous medium is characterized by a number of parameters including porosity , specific internal area (Z), tortuosity (τ) and permeability (m). These parameters are defined as follows. Given a unit square cell of dimension D, and particle diameter d, we have

$$p = 1 - \pi / 4 \, (d/D)^2 \tag{1.1}$$

$$z = 1/2 \, \pi \, d^2/D^3 \tag{1.2}$$

$$\tau = 1.4 \tag{1.3}$$

$$m = Sp^3/z^2 \tag{1.4}$$

Porosity, p, is defined as the ratio of void volume per volume of unit all . The specific internal area, Z, is the ratio of internal surface area to bulk volume . The tortuosity is defined as the ratio of the length of the flowpath of a fluid particle to the straight line distance.

The particle's size decreases as the carbon is consumed and all geometric properties which depend on particle diameter are functions of time and position . This model considers that the carbon matrix remains rigid as the particle diameter decreases and thus porosity increases with combustion.

The magnitude of REYNOLDS number defines the motion of the fluid which can be molecular , viscous or inertial. In the case of porous media , the flow is dominated by viscous and inertial effects. Darcy's Law for the range of REYNOLD's number where viscous effects dominate is the equation that governs the fluid flow in porous media. Two velocities which distinguish the flow through the medium are filter velocity Q, and pore velocity u. Filter velocity is given by :

$$Q = - m/\mu \; (\partial P/\partial x) \tag{1.5}$$

where u is the viscosity of the fluid and P is the pressure.

The pore velocity u is given by :

$$U = Q/p \tag{1.6}$$

The hypothesis of the Dupuit-Forcheimer assumption is that the local pore velocity is greater than the filter velocity. The actual velocity in a pore is a function of position within the pore . The Dupuit-Forcheimer relation defines an average velocity in a pore.

The model of combustion adopted was the model of N. N. Semenov (2). The relation of reaction rate to temperature and oxygen concentration, and the interaction of heat generation and heat transfer are fundamental to this model . If the heat transfer dominates, extinction will occur. If the heat generation dominates then combustion will result. The reaction rate equation was adopted from Arrhenius's Law for a simple reaction where the rate depends on the concentration of the reactants and not on the products. The heat generated by an exothermal reaction is obtained by multiplying the reaction rate by the heat of combustion .

A study of the curve of heat generation versus temperature presented by Frank-Kamenetskii distinguishes two phases during combustion. During the initial kinetic phase , the rate of reaction and the temperature are lowest. During This phase , there is an excess supply of oxygen. In the kinetic regime the reation rate increases exponentially with increasing temperature. The kinetic regime is followed by the diffusion regime. This phase is distinguished by high temperatures and reaction rates , and the reaction is limited by a lack of oxygen.

It is assumed that the chemical reaction for the combustion process produces carbon monoxide and carbon dioxide. The ratio of the mass rates of carbon monoxide to carbon dioxide depends on the temperature. Increasing temperature results in an increase of this CO to CO_2 ratio.

The model of heat transfer includes three basic mechanisms : convection , conduction and radiation . The heat transfer equation used by VATIKIOTIS (1) also includes a heat generation term due to combustion. All thermophysical properties were treated as temperatures dependent. These properties include viscosity, conductivity and density. Energy balance equations were constructed for control volumes of the porous medium and the air flowing through the porous medium .

A third field equation of the model was obtained by a mass balance of oxygen . This equation includes molecular diffusion, convective transport and a sink term to account for the depletion of oxygen due to combustion.

These equations resulted in a system of coupled, nonlinear transient field equation . These field equations, together with boundary and initial conditions , define the problem. They were solved numerically by using the Galerkin finite element method. Details of the formulation are presented in reference 1 .

II. EFFECT OF HEAT INPUT ON COMBUSTION

A. INTRODUCTION AND DESCRIPTION

In this section the effect of heat input on the combustion behavior of porous medium was investigated. The porous medium is subjected to a heat source on its surface . Two parameters of main importance are considered: The magnitude of the heat flux of the source to the porous medium (SQ), and the time that the heat flux remains active (TQ).

To do this analysis, all parameters of the system are fixed except the time period of heating (TQ) and the amount of heat flux (SQ).

The purpose of this section is to determine the relation between SQ and TQ which will result in combustion. This is achieved as follows:

. For a specific value of heat flux SQ, the program is run with different values of TQ until combustion occurs at $(TQ)_c$ and extinction occurs at $(TQ)_e$, whereδ is a small time period . Here we tookδ seconds .

$$TQ_c = TQ_e + \delta \tag{2.1}$$

Four cases of heat flux were studied in this section:

CASE II.1 SQ = 18000 BTU/ft.sq hr
CASE II.2 SQ = 20000 BTU/ft.sq hr
CASE II.3 SQ = 30000 BTU/ft.sq hr
CASE II.4 SQ = 40000 BTU/ft.sq hr

The fixed parameters used in all cases are:

Ambient temperature = 80 F
Ambient temperature = 2117 lb/ft.sq
Tortuosty = 1.400
Filament diameter = 0.0004167 ft

Thickness of matrix laminate = 0.0004167 ft
Thickness of porous medium = 0.02083 ft
Gas constant for air = 53.34 lbf ft/lbm R
Conductivity of filament = 86 BTU/lbm H.F.
Specific heat of filament = 0.703 lbm/Cf
Emissivity of filament = 0.90
Shape factor for int.HF.XFER coefficient = 1.00
Characteristc length of medium = 1 inch
Heat of reaction = 14090 BTU/Cf
Reaction order = 0.50
Stochiometric ratio (fuel/air) = 0.375
Reaction coefficient = 2065000 lbm/Cf H
Activation energy coefficient = 28840 deg R
Pressure differential across thickness = 50 lb/ft.sq
Initial carbon and air temperature = 80 F
Initial uniform oxygen concentration = 0.0172 lbm/ft.cu

The equations used in this program permit three sets of boundary conditions that are approximations to physical situations. The boundary conditions selected are the best approximations of a one dimensional model. The set of boundary conditions used in this case are typical of thermal flow reactor without radiation from the boundary surfaces . for the problems of this investigation, the following boundary conditions were used :

- No heat transfer from either end of the porous medium.

$$dt/dx = 0 \qquad \text{at} \quad X/L = 0 \quad \text{and} \quad X/L = 1 \qquad (2.2)$$

- Danckwerts' boundary conditions : Conditions for the air temperature and oxygen concentration were assumed. This means :

$$K_a \, \partial T_a/\partial x = \rho_a c_a u(T_a - T_\infty) \qquad X/L = 0 \qquad (2.3)$$

$$\partial T_a/\partial x = 0 \qquad X/L = 1 \qquad (2.4)$$

$$D_e \, \partial \phi \, / \partial x = u \, (\phi \, - \, \phi_{\cdot \infty}) \qquad X/L = 0 \qquad (2.5)$$

$$(K_e + K_r) \, \partial T_c/\partial x = -\sigma \, \varepsilon(T_c{}^4 - T^4{}_\infty) \qquad X/L = 1 \qquad (2.6)$$

$$K_a \partial T_a/\partial x = \rho_{\cdot a} c_a u(T_a \, - \, T_\infty) \qquad X/L = 1 \qquad (2.7)$$

$$\partial T_a/\partial x = 0 \qquad X/L = 1 \qquad (2.8)$$

$$D_e \partial \phi/\partial x = u(\phi \, - \, \phi_\infty) \qquad X/L = 1 \qquad (2.9)$$

B. PROCEDURE

For each case , the amount of heat flux (SQ) was fixed and several values of shut off time (TQ) were chosen until values of TQ_c and TQ_e were found such that :

$$TQ_c \approx TQ_e \qquad (2.10)$$

$$TQ_c = TQ_e + \delta \qquad (2.11)$$

where δ is a small number.

C. RESULTS

The results for each case were obtained in both numerical and graphical form . The behavior of carbon temperature, oxygen concentration and reaction rate for combustion and extinction are shown as surfaces versus time and position The program also calculates the air temperature in the porous medium. However the air temperature surfaces are not shown as they are quite similar , in most cases to carbon temperature.

There are three surface graphics for each heat flux case:

-Carbon temperature versus position and time
-Oxygen concentration versus position and time
-Reaction rate versus position and time

In adition , there are two curves for each heat flux (SQ) , one showing the variation of carbon temperature versus time for combustion and the other showing the variation of carbon temperature for extinction . These is two curves are for the point x/L=0. (i.e. where the air enters the porous medium) .

1. CASE II-1 SQ = 18000 BTU/ft.sq hr

The values for shut off time bounding extinction and combustion are :

for combustion TQ_c = 46 seconds
for extinction TQ_e = 47 seconds

During the transient analyses , system parameters varied . for each analysis , the maximum and minimum values of some of these parameters provide some insight into the character of the particular case . These parameters and their values are given in Table I

The graphical results are shown in Figures 2.1 to 2.6

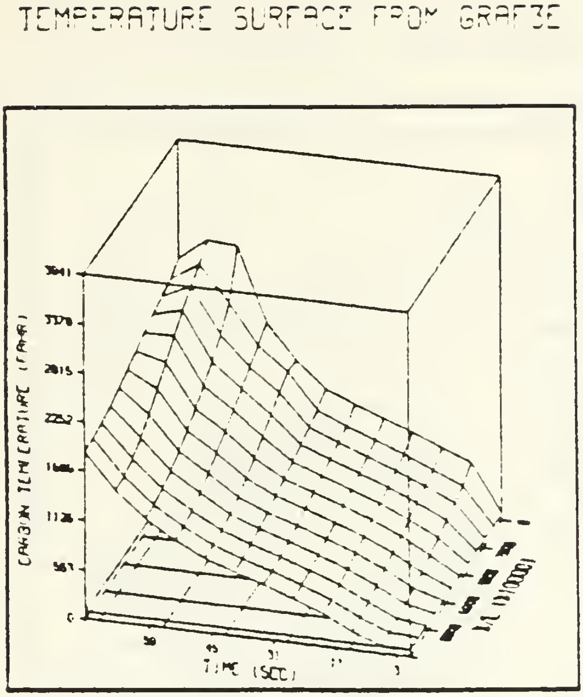


Figure 2.1 Temperature vs X/L and time for SQ = 18000 BTU/ft.sq hr and TQ = 46 seconds.

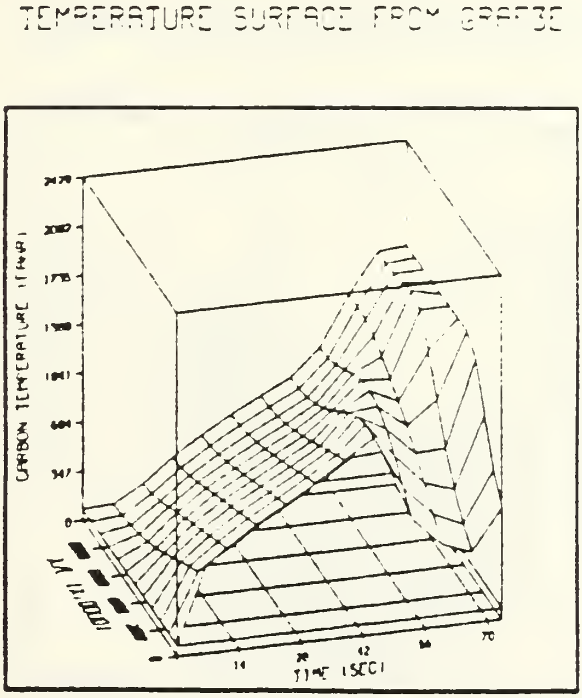


Figure 2.2 Temperature vs X/L and time for SQ = 18000 BTU/ft.sq hr and TQ = 45 seconds.

OXYGEN CONC. SURFACE FROM GRAF3E

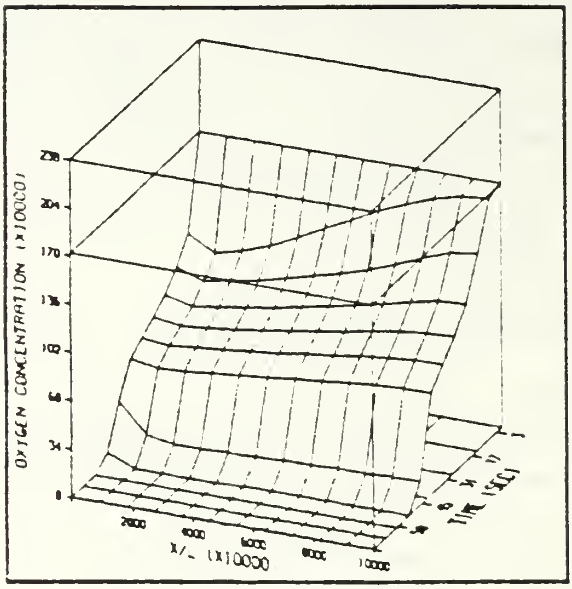


Figure 2.3 Oxygen concentration vs X/L and time for SQ = 18000 BTU/ft.sq hr and TQ = 46 seconds.

OXYGEN CONC. SURFACE FROM GRAF3E

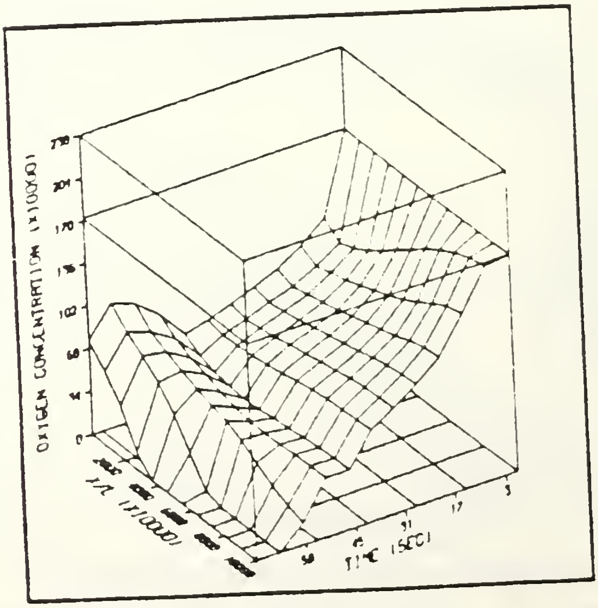


Figure 2.4 Oxygen concentration vs X/L and time for SQ = 18000 BTU/ft.sq hr and TQ = 45 seconds.

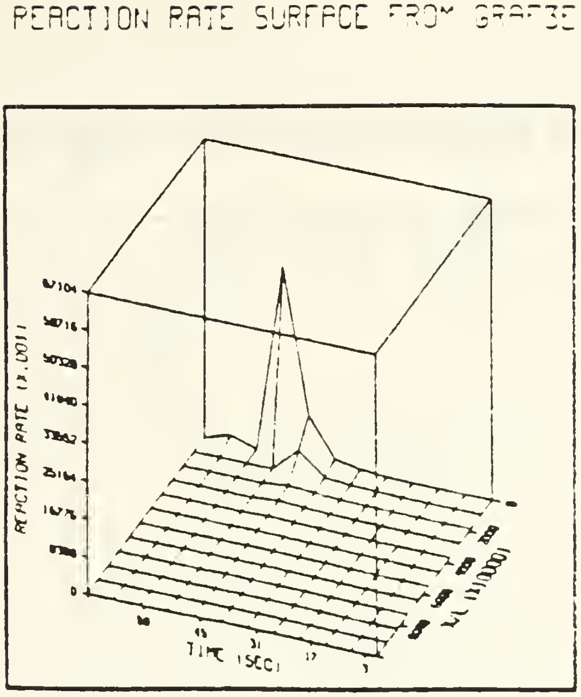


Figure 2.5 Reaction rate vs X/L and time for SQ =18000 BTU/ft.sq hr and TQ = 46 seconds.

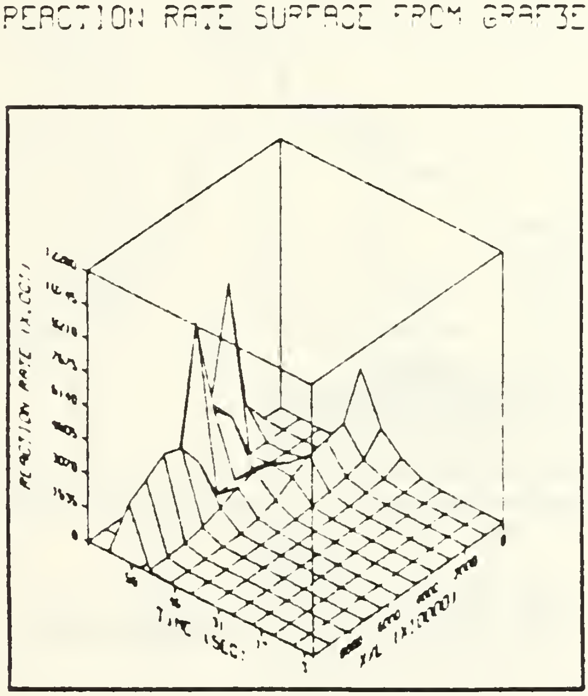


Figure 2.6 Reaction rate vs X/L and time for SQ = 18000 BTU/ft.sq hr and TQ = 45 seconds.

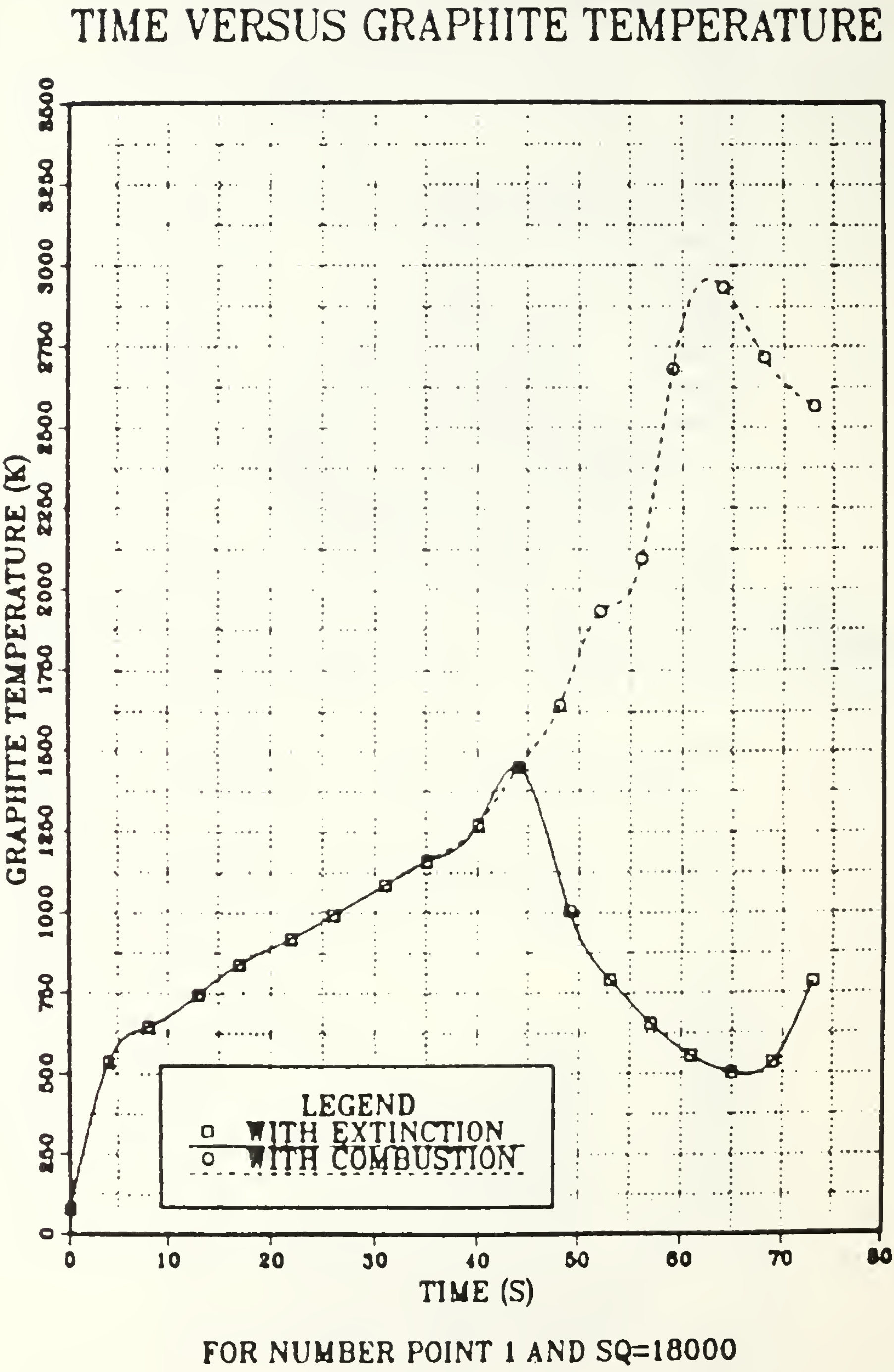


Figure 2.7 Combustion and extinction carbon temperature for position X/L = 0..

TABLE I

VARIED PARAMETERS DURING THE PROCESS FOR SQ = 18000 BTU/FT.SQ HR

parameters	extinction		combustion	
	maximum	minimum	maximum	minimum
permeability (ft.sq)(10^{-10})	2.022	1.617	298.8	1.617
pressure (lb/ft.sq)	2117	2066	2117	2066
pressure gradient (lb/ft.cu)	-1724	-3809	-716.6	-3384
pore velocity (ft/hr)	6707	4056	8676	2287
Reynolds number	1.477	0.0975	1.477	0.09243
convection coefficient	45.42	40.03	55.67	19.51

2. CASE II-2 SQ = 20000 BTU/ft.sq hr

For this case the heat flux duration times for the conditions of extinction and combustion are :

for combustion TQ_c = 35 seconds
for extinction TQ_e = 34 seconds

During the transient history of this case several parameters varied. The maximum and minimum of these changing variables are in the Table II . It is necessary to emphasize that these extrema results do not occur at the same time or same position (X/L). They are maximum and minimum values obtained at different times and position during the transient process. These values show the characteristc behavior of this case .

The behavior of carbon temperature , oxygen concentration and reaction rate are shown in Figures 2.8 to 2.13 . These surfaces are an important characteristic of this case because they show the evolution of the combustion process or extinction process for each position during the transient time .

3. CASE II-3 SQ = 30000 BTU/ft.sq hr

The values of heating time that result in combustion and extinction for this value of heat flux are :

for combustion TQ_c = 15 seconds
for extinction TQ_e = 14 seconds

During the transient analysis , some variation of values occured to several parameters. The limits of variation , maximum and minimum values , are shown in Table III . The process of combustion and extinction have particular characteristics that determine the variation of the values

TABLE II

VARIABLE PARAMETERS DURING THE PROCESS FOR SQ = 20000 BTU/FT.SQ HR

parameters	extinction		combustion	
	maximum	minimum	maximum	minimum
permeability (ft.sq)(10^{-10})	1.913	1.617	3.899	1.617
pressure (lb/ft.sq)	2117	2066	2117	2066
pressure gradient (lb/ft.cu)	-825.5	-3553	-17.65	-3706
pore velocity (ft/hr)	7472	2603	7488	2322
Reynolds number	1.477	0.155	1.477	0.041
convection coefficient	55.67	32.14	57.12	18.63

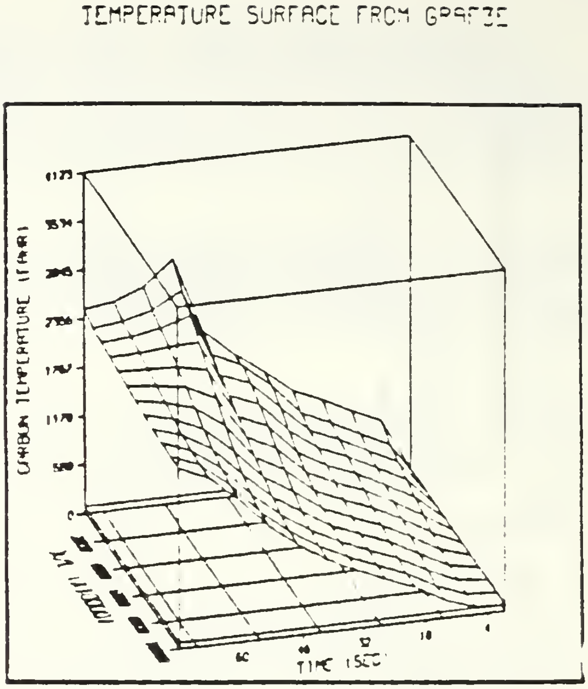


Figure 2.8 Temperature vs X/L and time for SQ = 20000 BTU/ft.sq hr and TQ = 35 seconds.

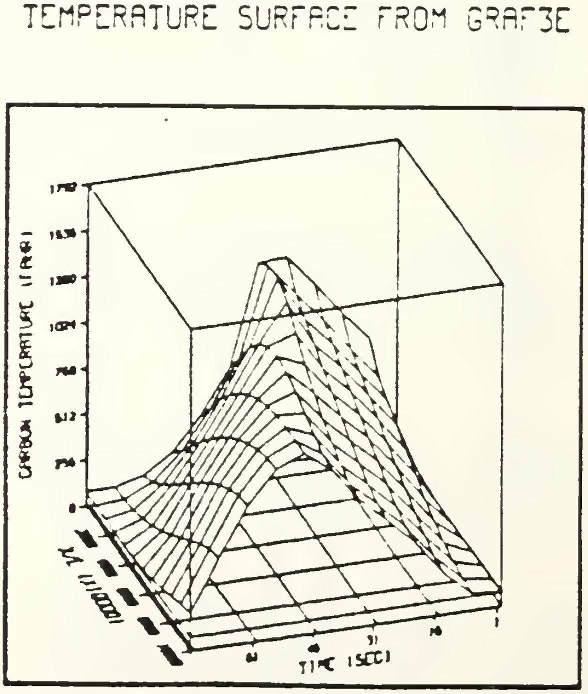


Figure 2.9 Temperature vs X/L and time for SQ = 20000 BTU/ft.sq hr and TQ = 34 seconds.

OXYGEN CONC. SURFACE FROM GRAF3E

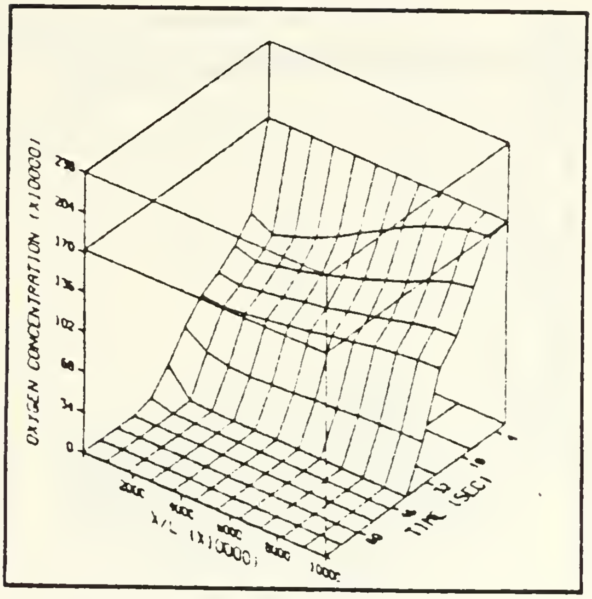


Figure 2.10 Oxygen concentration vs X/L and time for SQ = 20000 BTU/ft.sq hr and TQ = 35 seconds.

OXYGEN CONC. SURFACE FROM GRAF3E

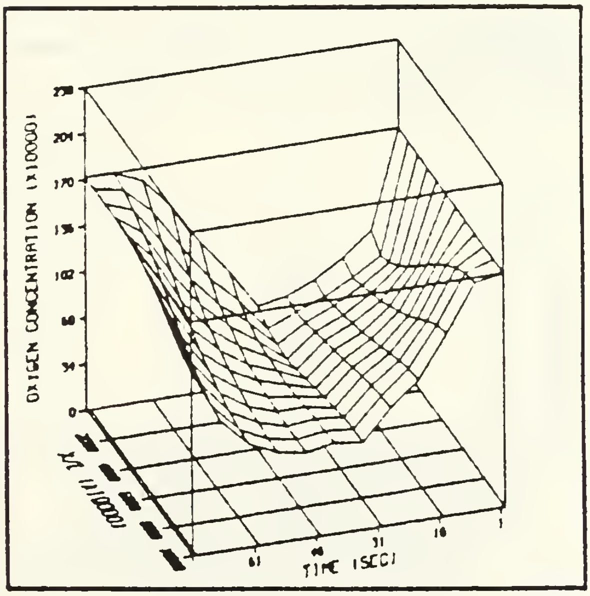


Figure 2.11 Oxygen concentration vs X/L and time for SQ = 20000 BTU/ft.sq hr and TQ = 34 seconds.

REACTION RATE SURFACE FROM GRAF3E

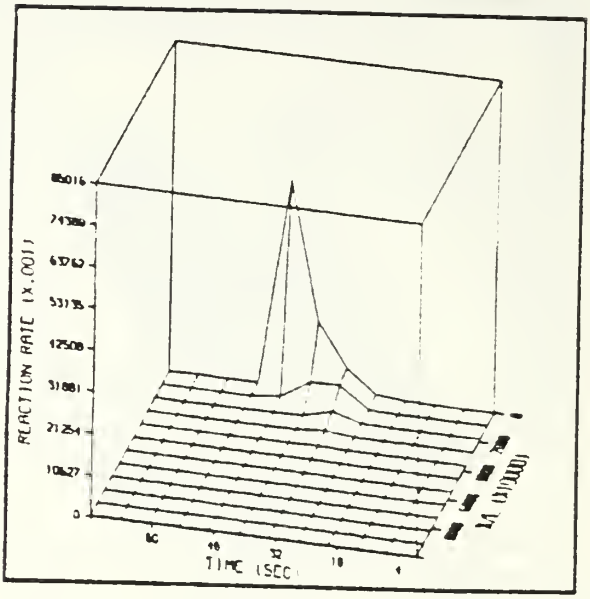


Figure 2.12 Reaction rate vs X/L and time for SQ = 20000 BTU/ft.sq hr and TQ = 35 seconds.

REACTION RATE SURFACE FROM GRAF3E

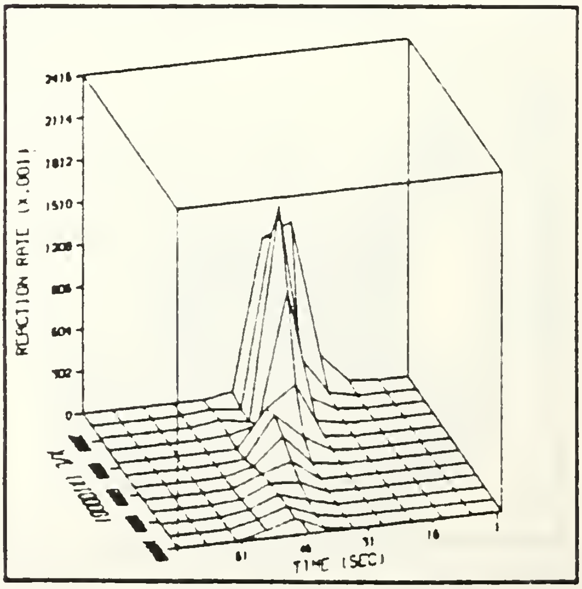


Figure 2.13 Reaction rate vs X/L and time for SQ =20000 BTU/ft.sq hr and TQ = 34 seconds.

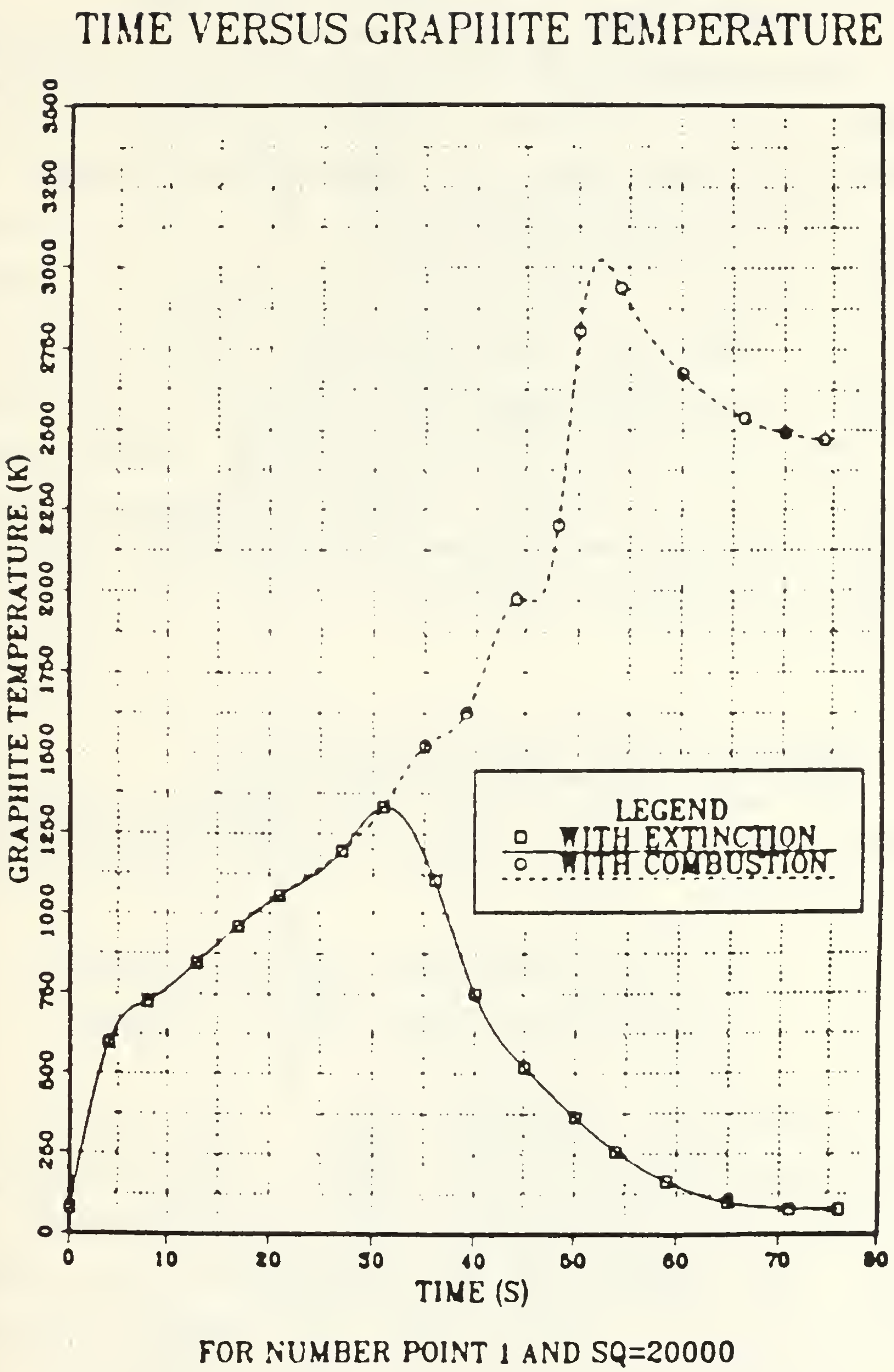


Figure 2.14 Extinction and combustion carbon temperature for position X/L = 0..

of these parameters. The maximum and minimum values give a general idea of system behavior . These limiting values do not occur at same position (X/L) or same time .

A better idea of the development of temperature , oxygen concentration and reaction rate can be obtained from Figures 2.15 to 2.20 These surfaces show the values of these parameters for each point (X/L) during the transient time .

Figure 2.14 shows that at X/L = 0. the transient behavior for extinction and combustion are the same until TQ_e = 14 seconds , the time the heat flux is terminated . After this time the temperature for the extinction case decreases to ambient temperature ; while for the combustion case , the temperature increases reaching a peak temperature of 3200 F at 28 seconds and thereafter decreases to an equilibrium combustion temperature of about 2500 F after about 50 seconds (see Figure 2.14).

4. CASE II-4 SQ = 40000 BTU/ft.sq hr

The heat flux of this case produced combustion and extinction of the porous medium at the following times :

for combustion TQ_c = 9 seconds
for extinction TQ_e = 8 seconds

During the transient process , the output of the program showed parameters th at didn't change with time and others that did . The variation of these parameter's values show the development of the combustion and extinction phenomenon for this value of SQ . The maximum and minimum values of several parameters are shown in Table IV . Again these values do not correspond to the same time .

The characteristics of this case , carbon temperature , oxygen concentration and reaction rate , as function

TABLE III

VARIED PARAMETERS DURING THE PROCESS FOR SQ = 30000 BTU/FT.SQ HR

parameters	extinction		combustion	
	maximum	minimum	maximum	minimum
permeability (ft.sq)(10^{-10})	2.022	1.617	2.948	1.617
pressure (lb/ft.sq)	2117	2066	2117	2066
pressure gradient(lb/ft.cu)	-841	-4850	-25.39	-4859
pere velocity (ft/hr)	9248	2475	9248	1852
Reynolds number	1.581	0.1932	1.477	0.037
convection coefficient	58.20	31.40	57.65	20.88

TEMPERATURE SURFACE FROM GRAF3E

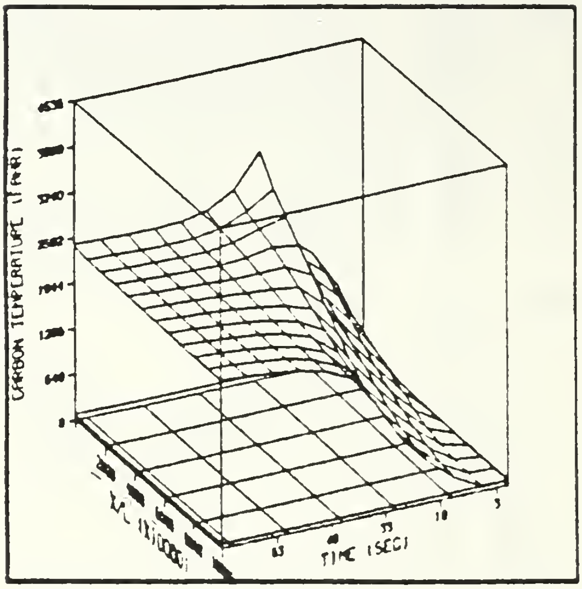


Figure 2.15 Temperature vs X/L and time for SQ = 30000 BTU/ft.sq hr and TQ = 15 seconds.

TEMPERATURE SURFACE FROM GRAF3E

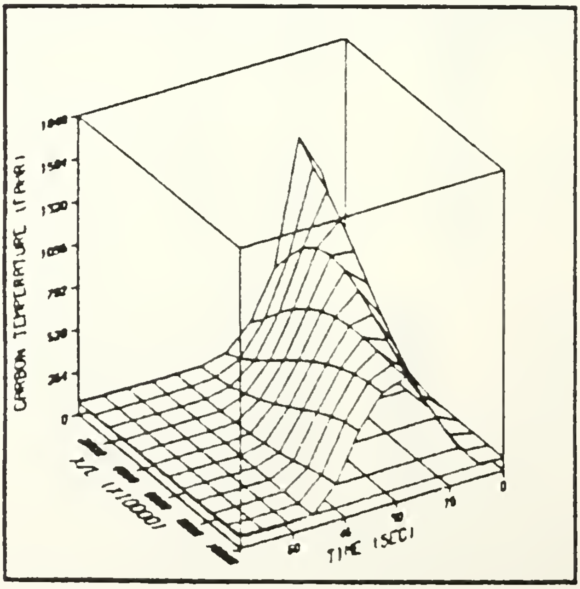


Figure 2.16 Temperature vs X/L and time for SQ = 30000 BTU/ft.sq hr and TQ = 14 seconds.

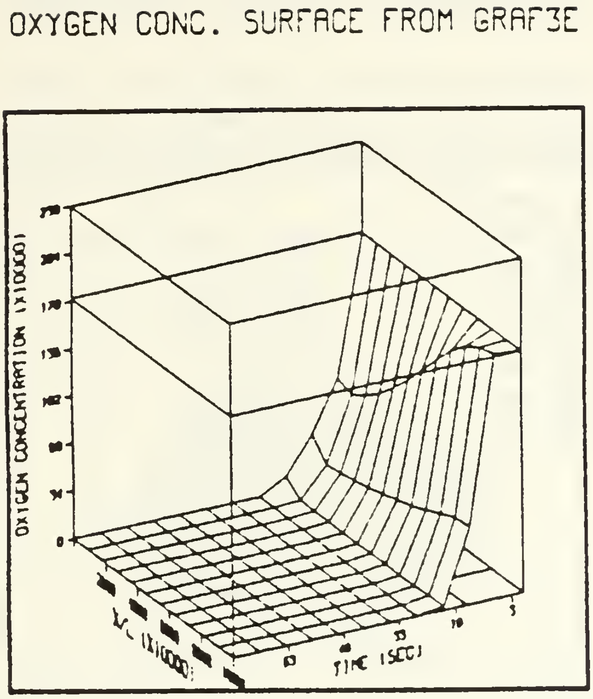


Figure 2.17 Oxigen concentration vs X/L and time for SQ =30000 BTU/ft.sq hr and TQ = 15 seconds.

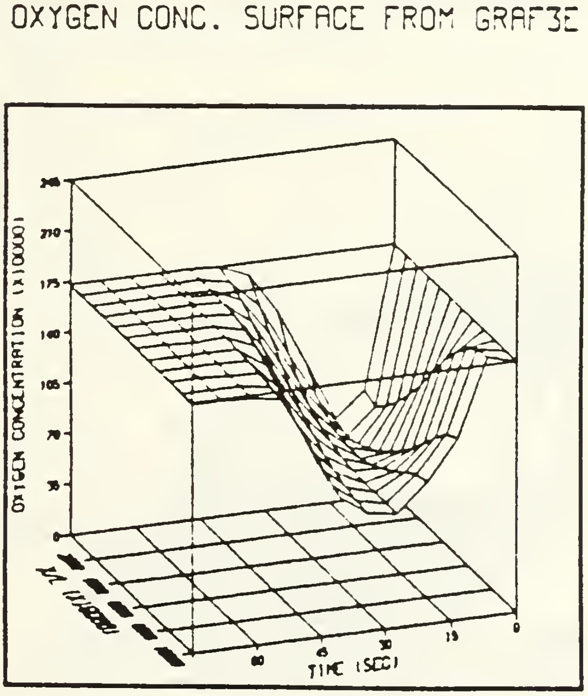


Figure 2.18 Oxigen concentration vs X/L and time for SQ = 30000 BTU/ft.sq hr,and TQ = 14 seconds.

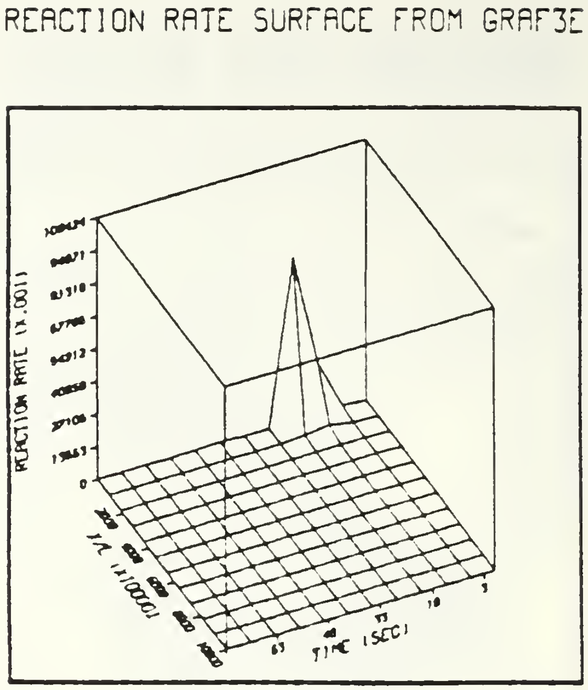


Figure 2.19 Reaction rate vs X/L and time for SQ = 30000 BTU/ft.sq hr and TQ = 15 seconds.

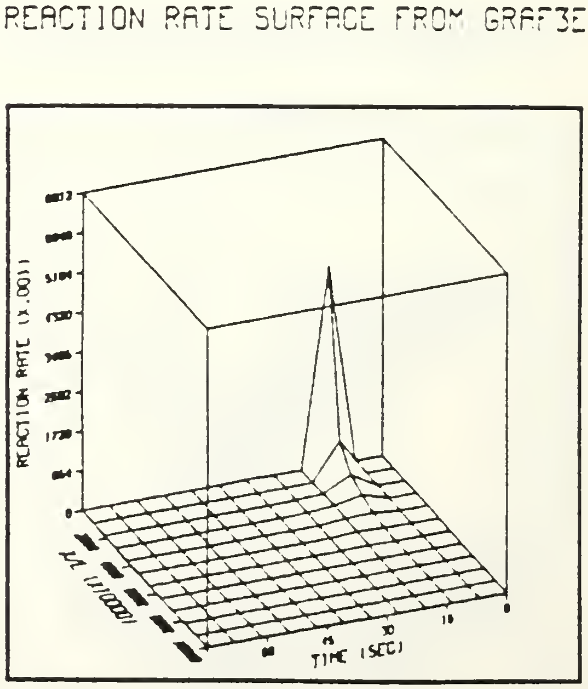


Figure 2.20 Reaction rate vs X/L and time for SQ = 30000 BTU/ft.sq hr and TQ = 14 seconds.

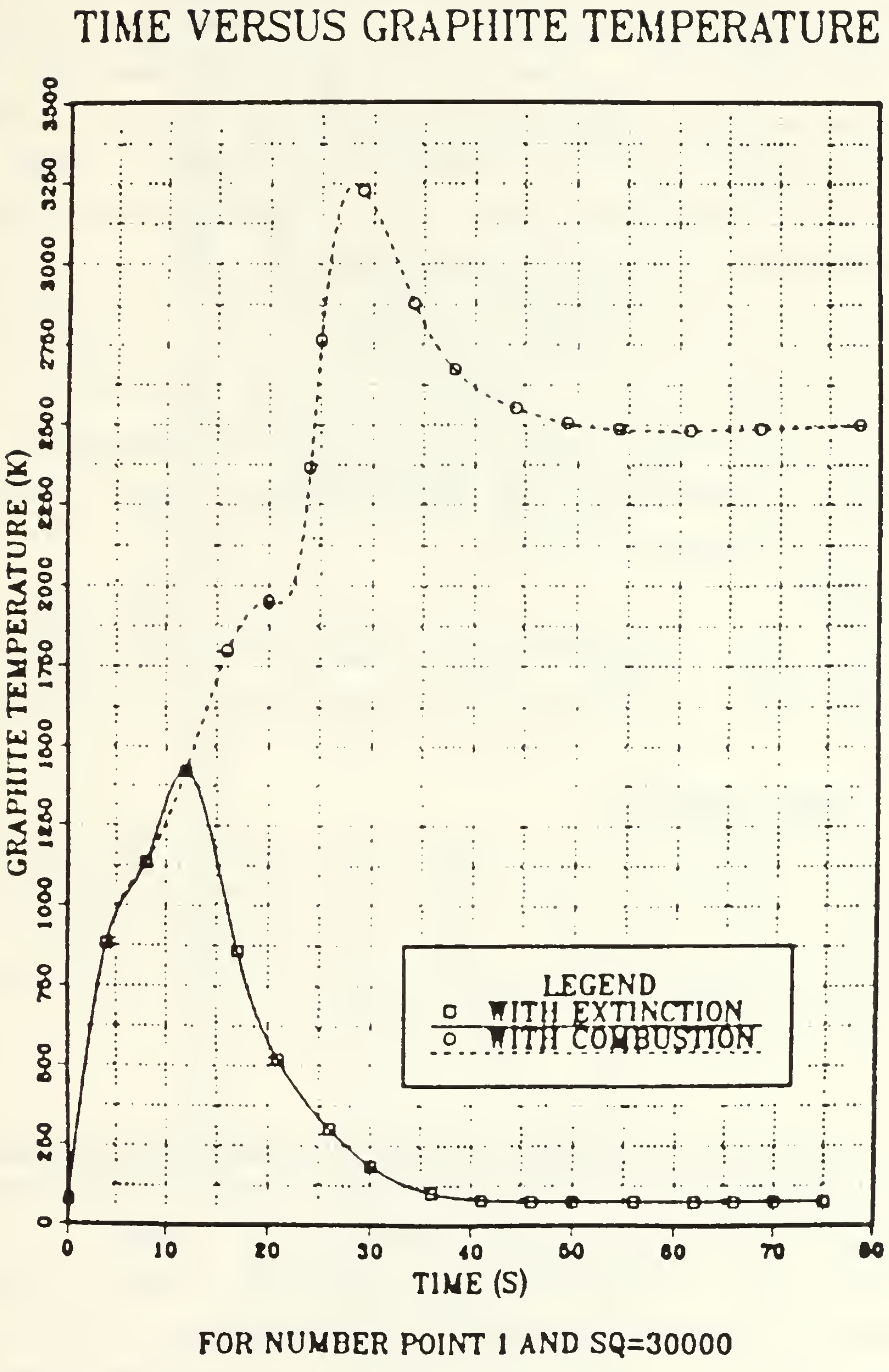


Figure 2.21 Extinction and combustion carbon temperature for position X/L = 0..

of time and position (X/L) are shown as graphic surfaces in Figures 2.22 to 2.27 . These graphical results give an idea about the behavior of each point of the transient history .

For X/L = 0 , both the combustion and extinction cases show similar behavior to this time equal to about 8 seconds , when the heat flux is terminated . After this time, for the extinction case , the temperature decreases to ambient temperature . For the combustion case , the temperature at X/L = 0 increased to about 3300 F , and thereafter decreased to around 2500 F (temperature of combustion) . Both the extinction and combustion cases achieve new equilibrium temperatures , about 2500 F for the combustion cases and ambient temperature for the extinction cases , after 35 seconds (see Figures 2.28).

D. SUMMARY

Here , some observations are made about the effects of heat flux input and duration of heat flux on the combustion process.

1. Power Relation

For each case , a pair of values $(SQ,(TQ)_c)$ was obtained . A plot of these point is shown in Figures 2.29 and 2.30 . It is observed that the relation between SQ and TQ of these graphics yields the approximate power relation (equation 2.12) .

2. Relation of Temperature and Oxygen Concentration

During the initial heating of the porous medium , the temperature increases while the oxygen is being defleted. After the heat flux is removed , either extinction or combustion will proceed. If extinction occurs , the carbon temperature decreases to ambient temperature while the oxygen is being restored to ambient concentreition .

If combustion occurs ,then the oxygen inside the medium goes to zero and remains there . The only oxygen

TABLE IV

VARIED PARAMETERS DURING THE PROCESS FOR SQ = 40000 BTU/FT.SQ HR

parameters	extinction		combustion	
	maximum	minimum	maximum	minimum
permeability (ft.sq)(10^{-10})	2.186	1.617	307.3	1.677
pressure (lb/ft.sq)	2117	2066	2117	2066
pressure gradient (lb/ft.cu)	-823.9	-5705	-25.79	-5705
pore velocity (ft/hr)	8945	2061	9597	1480
Reynolds number	1.581	0.1929	1.477	0.0365
convection coeffitient	58.00	29.33	58.00	23.19

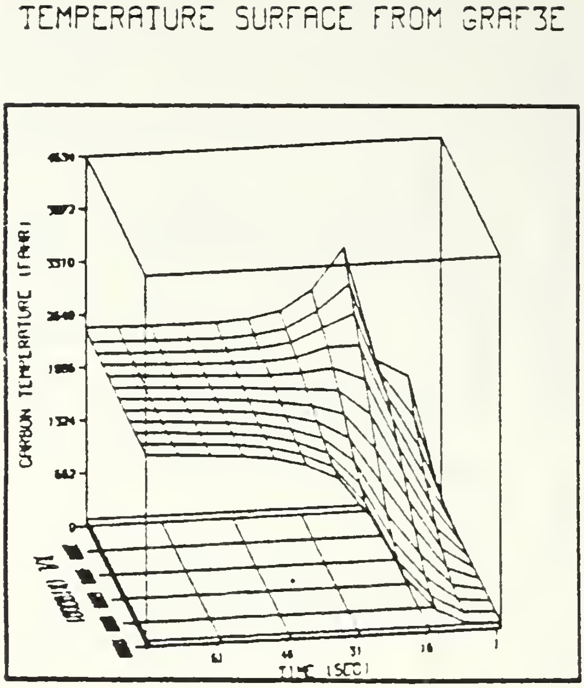


Figure 2.22 Temperature vs X/L and time for SQ = 40000 BTU/ft.sq hr and TQ = 9 seconds.

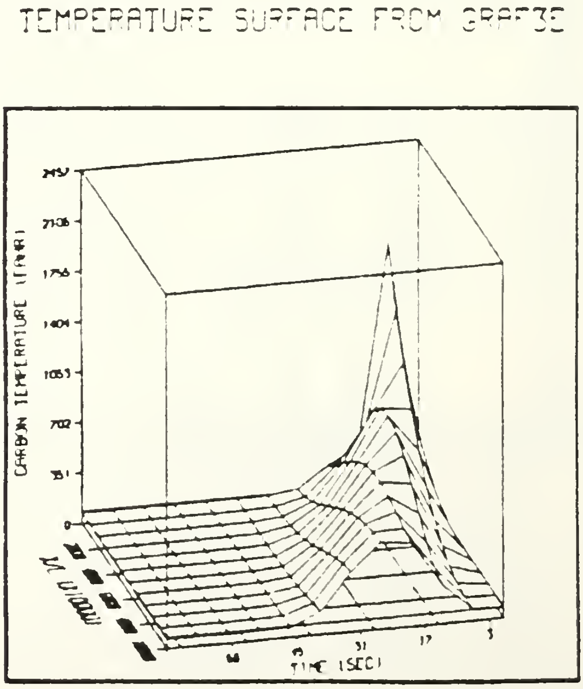


Figure 2.23 Temperature vs X/L and time for SQ = 40000 BTU/ft.sq hr and TQ = 8 seconds.

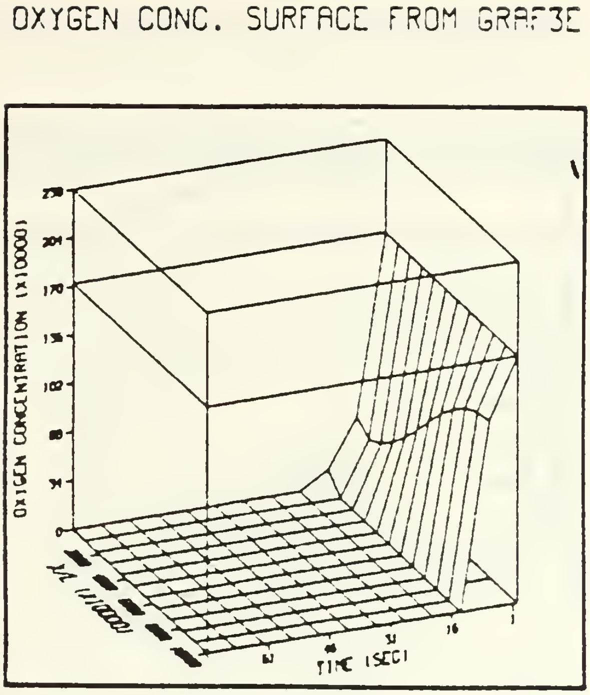


Figure 2.24 Oxygen concentration vs X/L and time for SQ = 40000 BTU/ft.sq hr and TQ = 9 seconds.

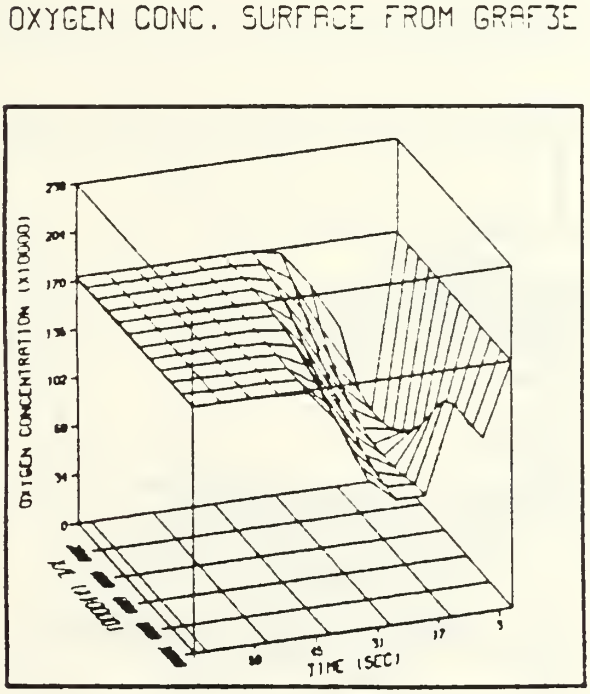


Figure 2.25 Oxigen concentration vs X/L and time for SQ = 40000 BTU/ft.sq hr and TQ = 8 seconds.

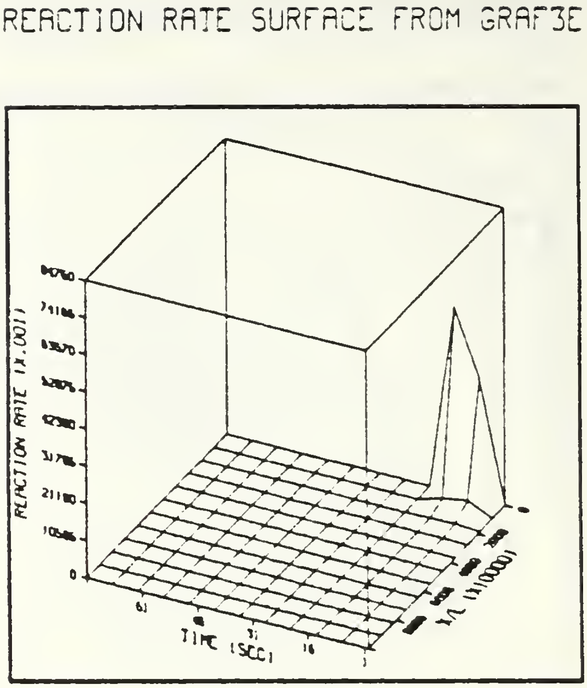


Figure 2.26 Reaction rate vs X/L and time for SQ = 40000 BTU/ft.sq hr and TQ = 9 seconds.

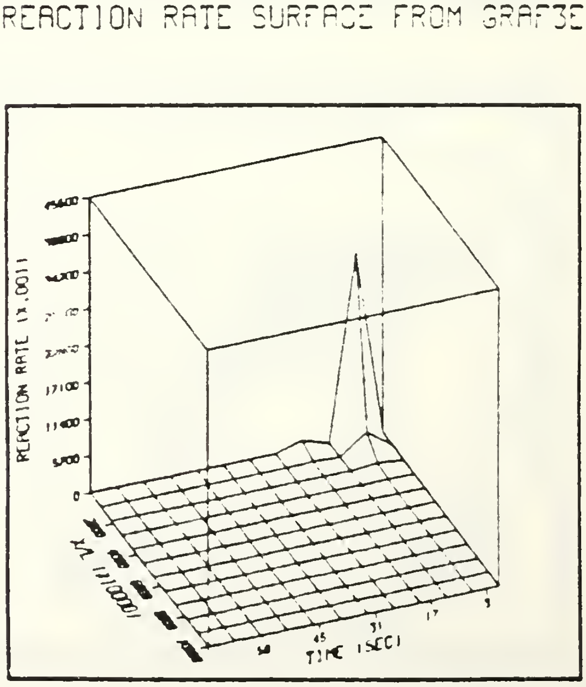


Figure 2.27 Reaction rate vs X/L and time for SQ = 40000 BTU/ft.sq hr and TQ = 8 seconds.

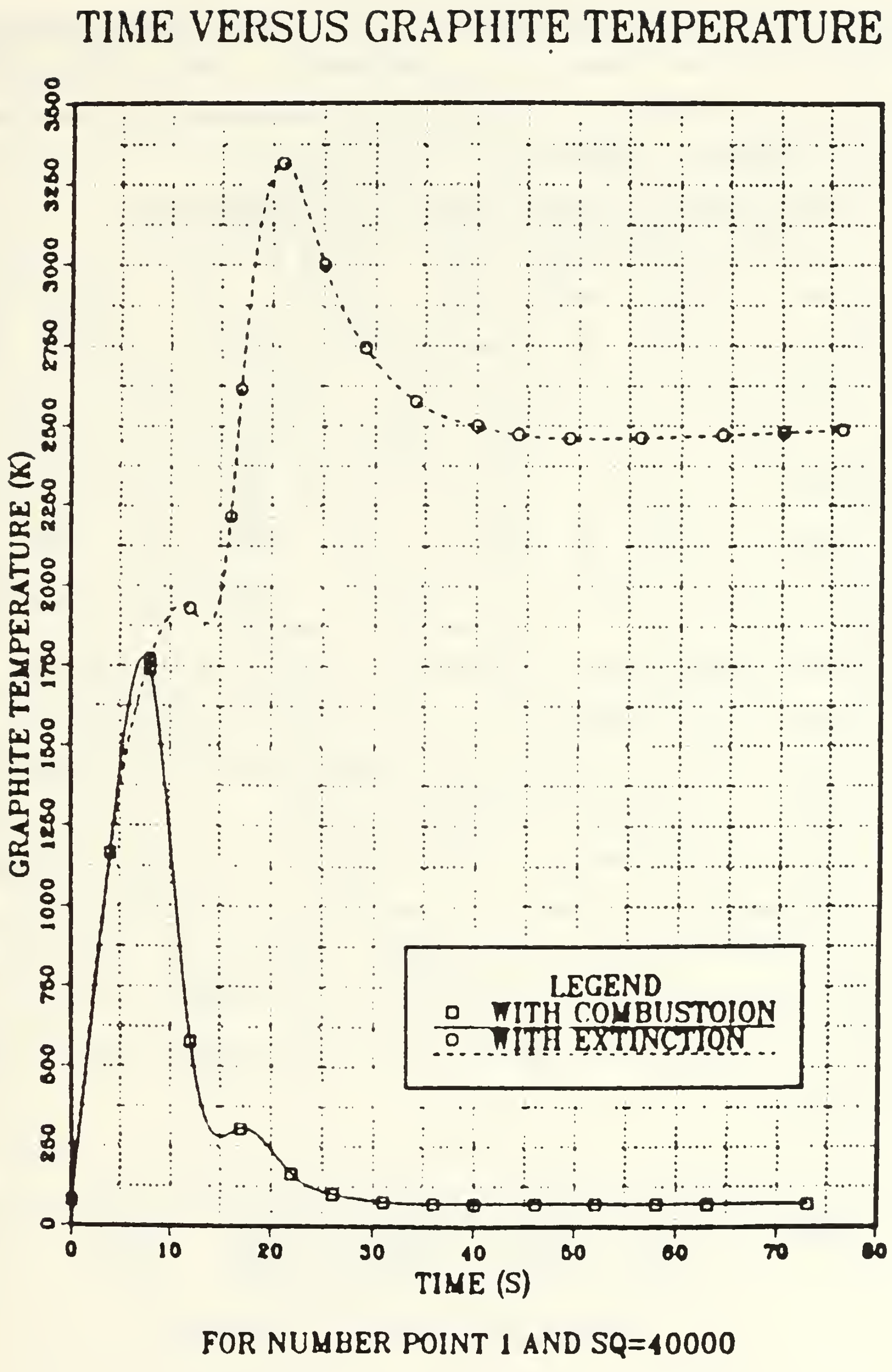


Figure 2.28 Extinction and combustion carbon temperature for position X/L = 1.

$$TQ_c = 3.4\ 10^{10}/(SQ)^{2.09} \qquad (2.12)$$

present is at the entrance at X/L = 0 . The temperature continues to increase to a maximum , and thereafter the temperature decreases . Eventually the entire medium would achieve a uniform combustion temperature .

3. Equilibrium Temperature for Combustion

In all combustion cases , the behavior was similar . During the initial combustion period , the temperature of the medium at X/L = 0 rose between 2000 F (CASE II-1) to 3400F (CASE II-4) . At this time , on the other side of the medium at X/L = 1. , the temperature of the medium was approximately 1500 F . This during thus early transient stage there is aΔT of 1300 F (for CASE II-1) and 1900 F (for CASE II-4) across the medium . As time proceeds the temperature at X/L = 0 decreased , while at X/L = 1. , the temperature increased . That is , with progressing time , the medium moves towards a uniform temperature . In the present case , this equilibrium temperature of combustion is around 2400 F to 2500 F for all cases .

The mechanism of equilibrium of the temperature during combustion is due to the heat transfer by air . As the air flows through the porous medium it transports the heat from the hot front part of the medium to the cooler back part , until all points of the medium have the same temperature .

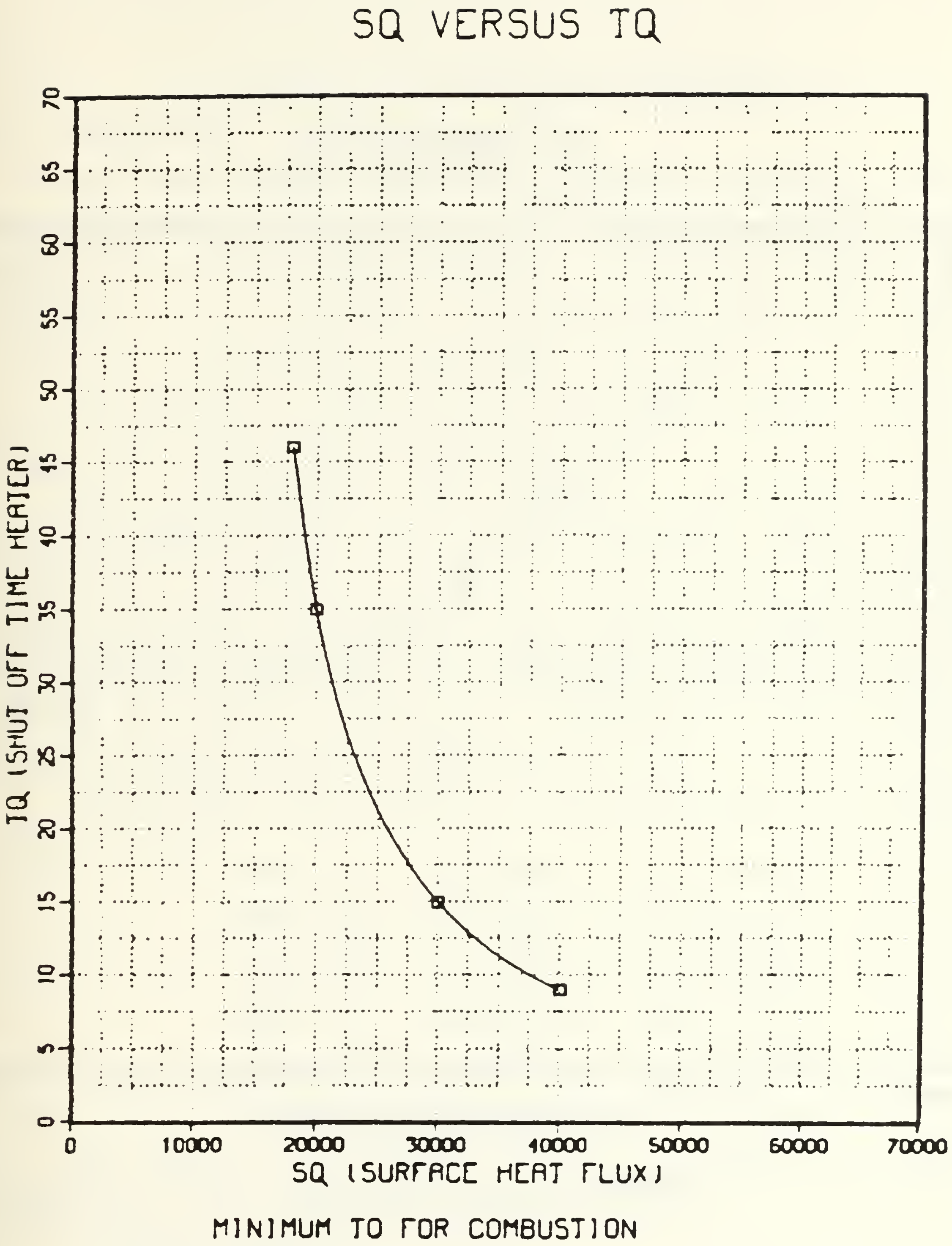


Figure 2.29 Heat flux versus combustion temperature (TQ_c) rectangular plot.

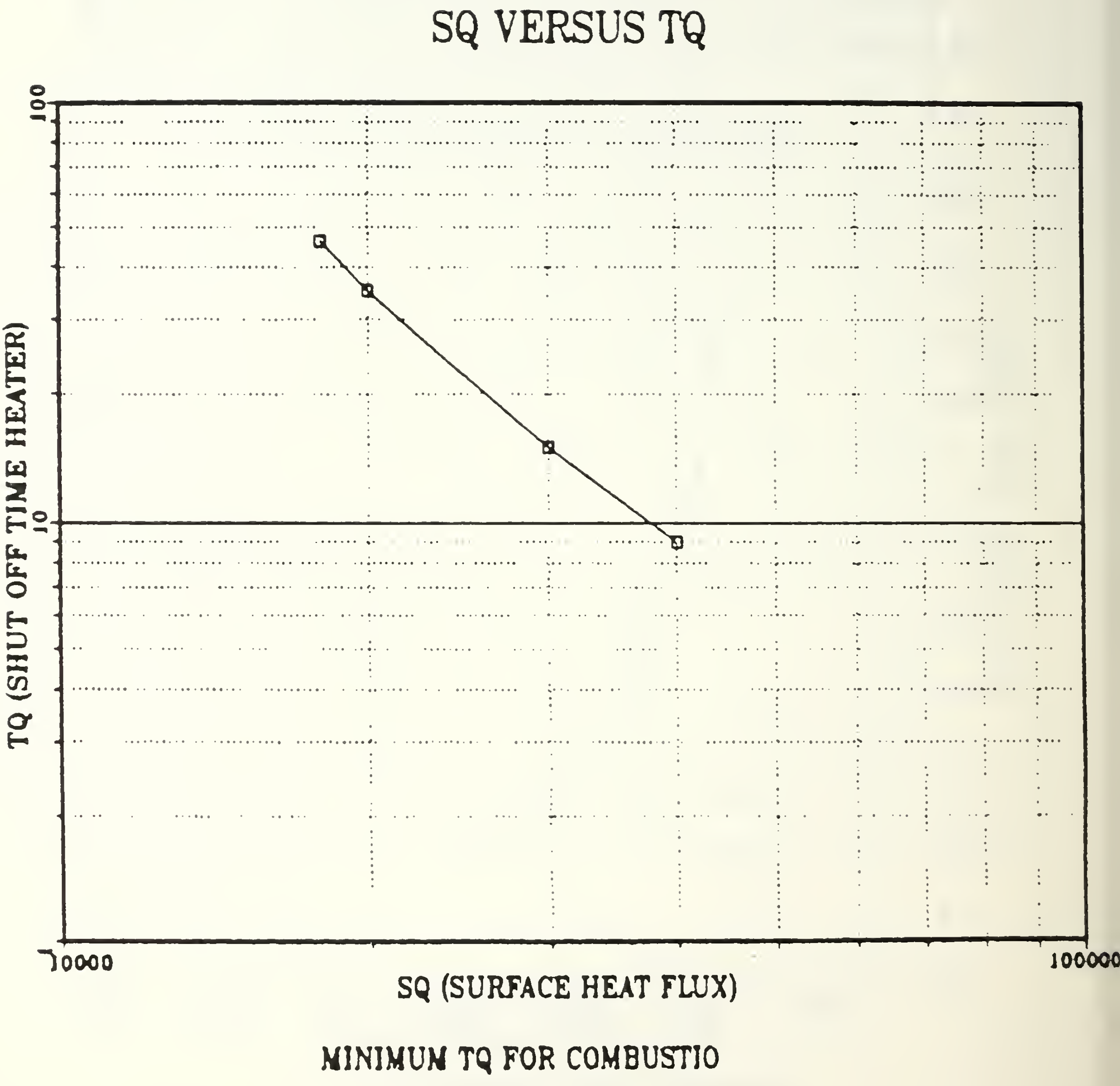


Figure 2.30 Heat flux (SQ) vs combustion temperature(TQ_c) Log log plot.

III. EFFECT OF THICKNESS ON COMBUSTION

A. INTRODUCTION

The porous medium has several geometric parameters that can have direct influence on the combustion process. The effect of the thickness parameter on system behavior is analysed in this section. All other parameters are fixed except the thickness of the medium.

The purpose of this section is to determine the relation of the thickness on the minimum temperature to start combustion (i.e., the ignition temperature).

For a specified value of thickness, the program is run with different values of initial temperature. This initial temperature is equal at all points of the medium. The lowest value of initial temperature that results in combustion is the ignition temperature Tc. Extinction occurs at Tc-δ , whereδ is a small increment of temperature. The value ofδ used in this parametric analysis was 10 F .

Seven cases with different thicknesses were studied in this section:

CASE III-1 THICKNESS = 0,25 inches
CASE III-2 THICKNESS = 0,50 inches
CASE III-3 THICKNESS = 0,75 inches
CASE III-4 THICKNESS = 1.00 inches
CASE III-5 THICKNESS = 2.00 inches
CASE III-6 THICKNESS = 4.00 inches
CASE III-7 THICKNESS = 6.00 inches

Each case is characterised by its thickness. The fixed parameters used in all cases are:

- Ambient temperature = 80 F
- Ambient pressure = 2117 lb/ft. sq.
- Tortuosity = 1.400
- Filament diameter = 0.0004167 ft.

- Thickness of matrix laminate = 0.0004167 ft.
- Thickness of porous medium = 0.02083 ft.
- Gas constant for air = 53.34 lbf.ft/lbm.R
- Conductivity of filament = 86 BTU/lbf HF
- Specific heat of filament = 0.703 lbm/cf.
- Emissivity of filament = 0.90
- Shape factor for int.HF.XFER coefficient = 1.00
- Heat of reaction = 14090 BTU/CF
- Reaction order = 0.50
- Stoichiometric ratio (full/air) = 0.375
- Reaction rate coefficient = 2065000 lbm/CF hr
- Activation energy coefficient = 28.840 deg R
- Pressure differential across thickness = 50 lb/ft^3
- Initial uniform oxygen concentration = 0.0172 lbm/ft^3

B. PROCEDURE

For each case, the characteristic length of the medium (thickness) was fixed and values of the uniform initial temperature were chosen until the value of temperature for combustion (T_c) and temperature for extinction (T_e) were approximately equal ($T_c \approx T_e$) or ($T_c = T_e + 10$) (F) .

C. RESULTS

For each case, the results were obtained in both numerical and graphical form. The behavior of carbon temperature, oxygen concentration and reaction rate for combustion and extinction are shown as surfaces versus time and position.

The numerical results from the program show the variation of several parameter values during the transient analysis. The air temperature inside the porous medium, the griphite temperature and the oxygen concentration are presented at each position (X/L) at intervals of time. Other system properties are also given . These properties characterize the process of combustion and extinction for different thicknesses. The maximum and minimum do not occur at the same point or at the same time.

The graphical results are given in the form of surfaces. These surfaces show the behavior of carbon temperature, oxygen concentration and reaction rate versus time and position (X/L) for the combustion and extinction processes.

1. CASE III-1 Thickness = 0.25 inches

The values of the initial uniform carbon temperature bounding the extinction and combustion processes are:

for combustion Tc = 1100 F
for extinction Te = 1090 F

The development with time of the behavior of the graphite temperature, oxygen concentration and reaction rate during the combustion and extinction processes are shown in Figures 3.1 to 3.6 The transient parametric analysis provide some insight into the characterers of this particular case. The maximum and minimum values of these parameters are given in Table V .

2. CASE III-2 Thickness = 0.50 inches

The combustion and extinction process, in this case, start with the following uniform carbon temperatures:

for combustion Tc = 960 F
for extinction Te = 950 F

For this case, the graphical results for graphite temperature, oxygen concentration and reaction rate are shown in Figures 3.7 to 3.12 . The characteristics of the changing parameters in this case, are shown by the maximum and minimum values in Table VI .

TEMPERATURE SURFACE FROM GRAF3E

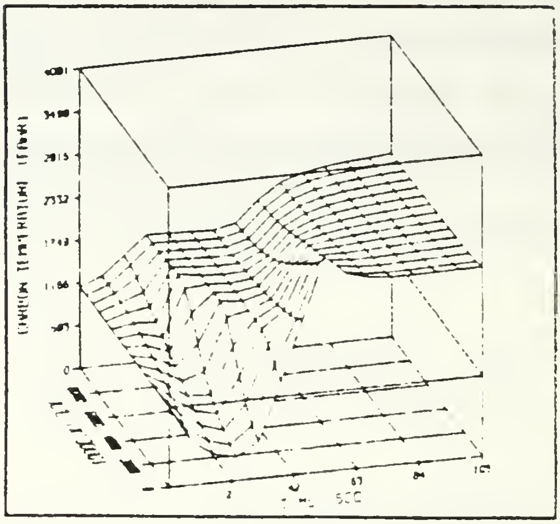


Figure 3.1 Temperature vs X/L and time
for thickness = 0.25 in
Initial carbon temperature = 1100 F.

TEMPERATURE SURFACE FROM GRAF3E

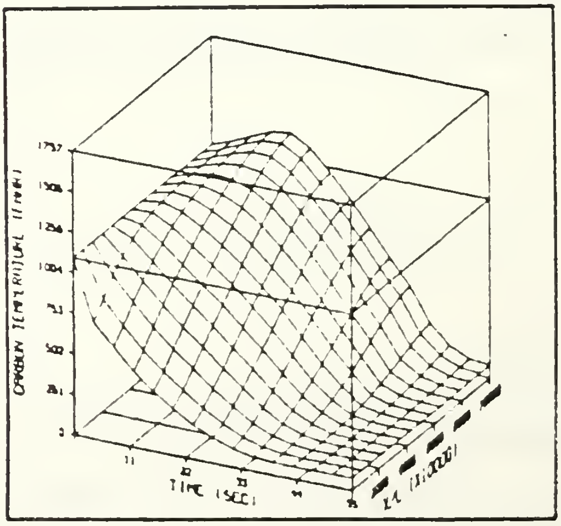


Figure 3.2 Temperature vs X/L and time
for thickness = 0.25 in
Initial carbon temperature = 1090 F.

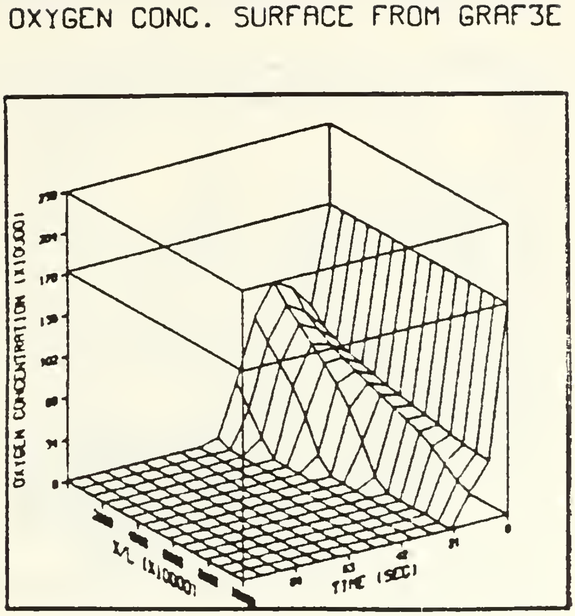


Figure 3.3 Oxygen concentration vs X/L and time
for thickness = 0.25 in
Initial carbon temperature = 1100 F.

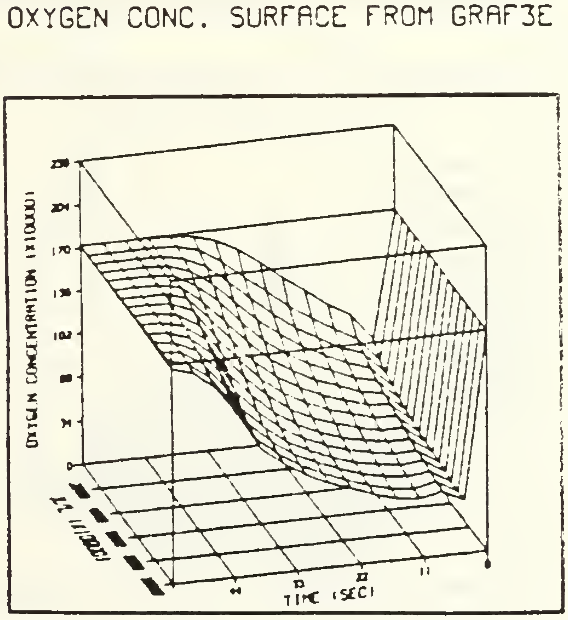


Figure 3.4 Oxygen concentration vs X/L and time
for thickness = 0.25 in
Initial carbon temperature = 1090 F.

REACTION RATE SURFACE FROM GRAF3E

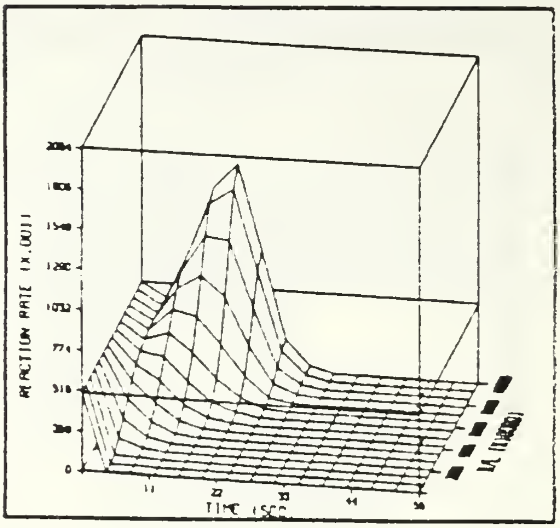


Figure 3.5 Reaction rate vs X/L and time
for thickness = 0.25 in
Initial carbon temperature = 1100 F.

REACTION RATE SURFACE FROM GRAF3E

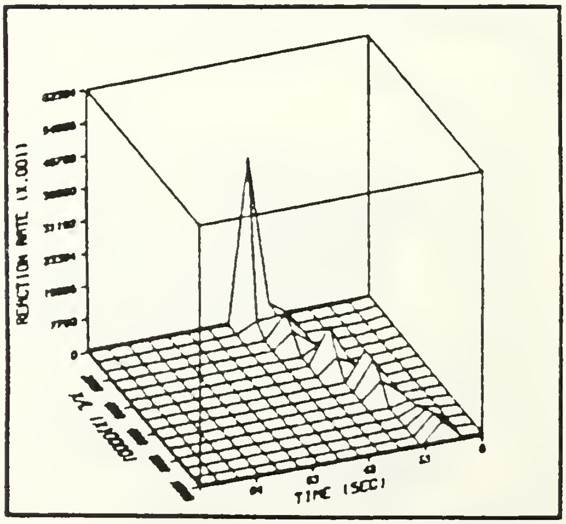


Figure 3.6 Reaction rate vs X/L and time
for thickness = 0.25 in
Initial carbon temperature = 1090 F.

TABLE V

VARIED PARAMETERS DURING THE PROCESS FOR THICKNESS = 0.25 INCHES

parameters	extinction		combustion	
	maximun	minimun	maximun	minimun
permeability (ft.sq)(10^{-10})	1.772	1.618	1.842	1.617
pressure (lb/ft.sq)	2117	2066	2117	2066
pressure gradient (lb/ft.cu)	-935	-3807	-742	-4132
pore velocity (ft/hr)	8595	2633	6654	1622
Reynolds number	0.1522	0.1357	0.202	0.065
convection coefficient	56.07	31.05	42.03	29.71

TEMPERATURE SURFACE FROM GRAF3E

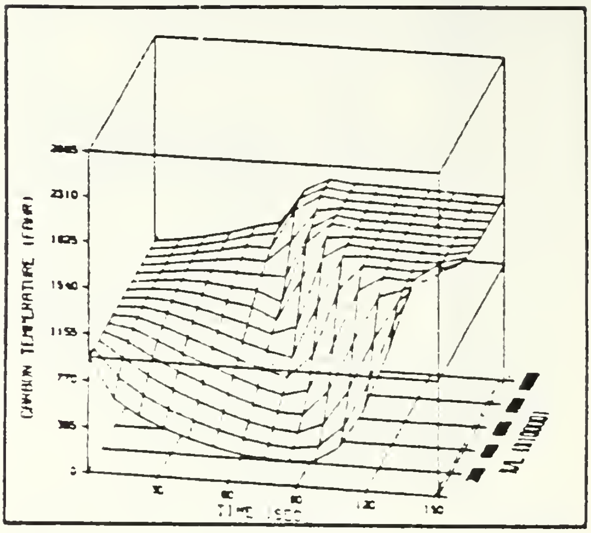


Figure 3.7 Temperature vs X/L and time
for thickness = 0.50 in
Initial carbon temperature = 960 F.

TEMPERATURE SURFACE FROM GRAF3E

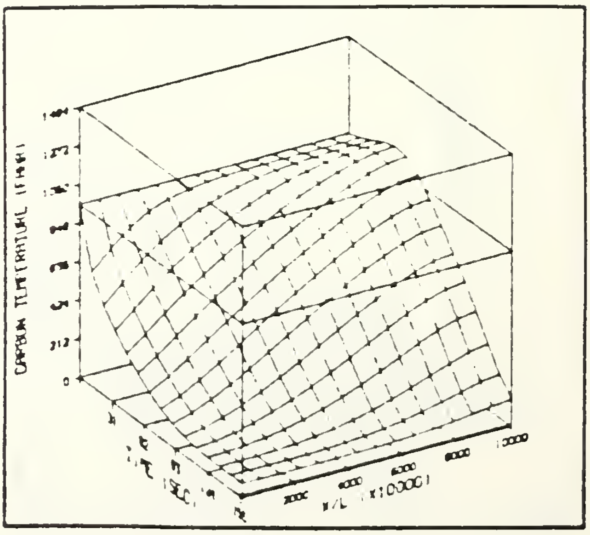


Figure 3.8 Temperature vs X/L and time
for thickness = 0.50 in
Initial carbon temperature = 950 F.

OXYGEN CONC. SURFACE FROM GRAF3E

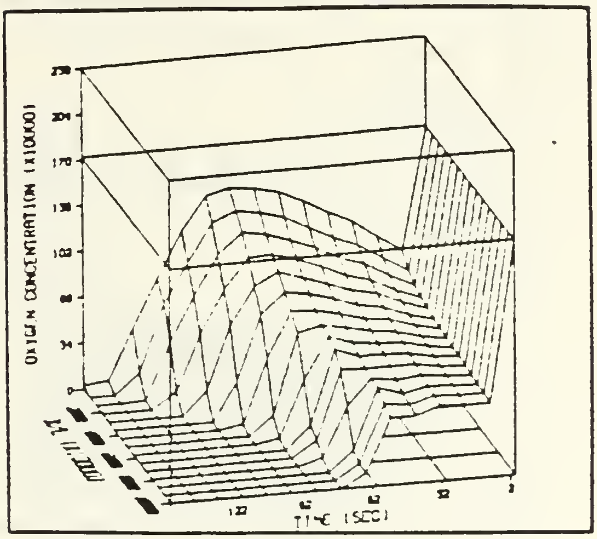


Figure 3.9 Oxygen concentration vs X/L and time for thickness = 0.50 in
Initial carbon temperature = 960 F.

OXYGEN CONC. SURFACE FROM GRAF3E

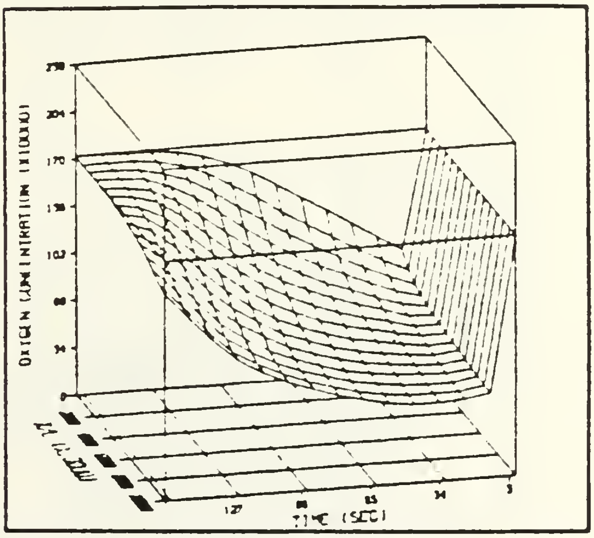


Figure 3.10 . Oxygen concentration vs X/L and time for thickness = 0.50 in
Initial carbon temperature = 950 F.

REACTION RATE SURFACE FROM GRAF3D

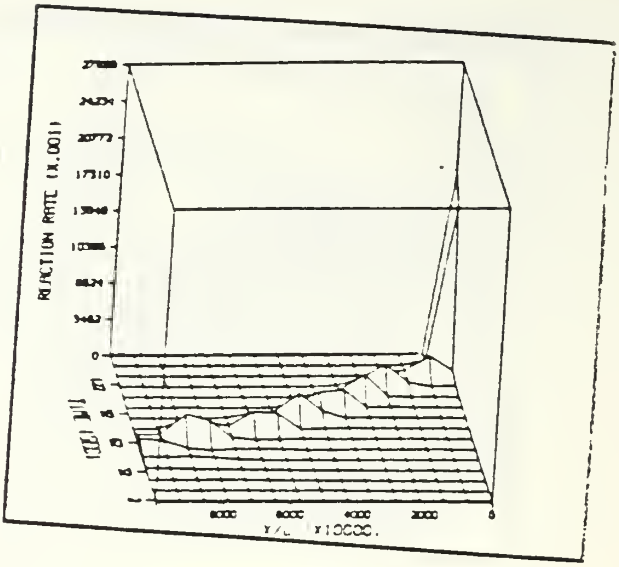


Figure 3.11 Reaction rate vs X/L and time for thickness = 0.50 in
Initial carbon temperature = 960 F.

REACTION RATE SURFACE FROM GRAF3D

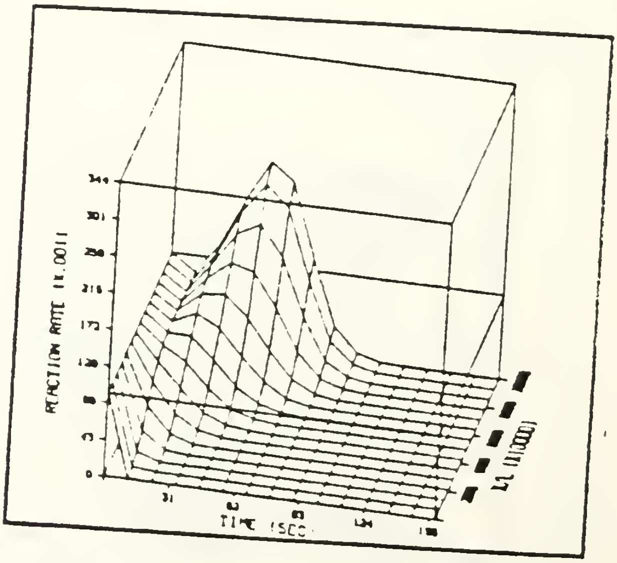


Figure 3.12 Reaction rate vs X/L and time for thickness = 0.50 in
Initial carbon temperature = 950 F.

TABLE VI

VARIED PARAMETERS DURING THE PROCESS FOR THICKNESS = 0.50 INCHES

parameters	extinction		combustion	
	maximun	minimun	maximun	minimun
permeability (ft.sq)(10^{-10})	1.685	1.617	1.767	1.617
pressure (lb/ft.sq)	2117	2066	2117	2066
pressure gradient (lb/ft.cu)	-492	-1896	-325	-2039
pore velocity (ft/hr)	4431	1328	3372	933
Reynolds number	0.711	0.085	0.1575	0.0446
convection coefficient	41.07	23.62	34.04	20.78

3. CASE III-3 Thickness = 0.75 inches

During this case the minimum uniform temperature that starts the combustion process and the maximum uniform temperature for extinction are:

for combustion Tc = 900 F
for extinction Te = 890 F

During the transient analysis, the system parameters varied. For this case , the maximum and minimum values of some of these parameters provide some insight into the character of the case. These parameters and their extreme values are given in Table VII .

Figures 3.13 to 3.18 show the graphical results for carbon temperature, oxygen concentration and reaction rate for this case.

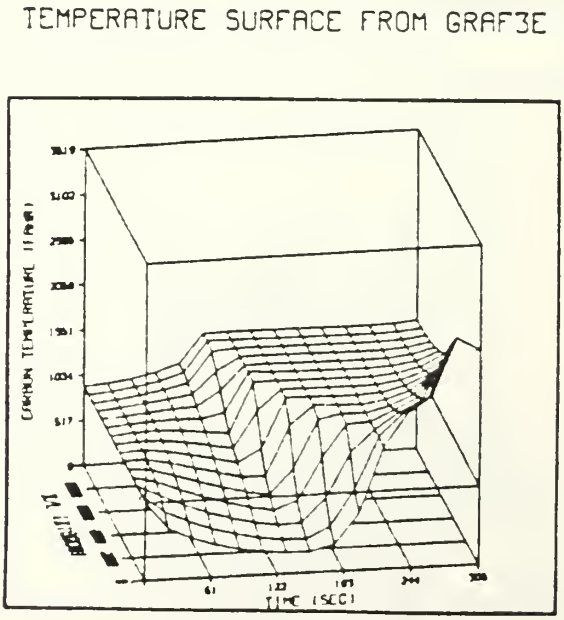


Figure 3.13 Temperature vs X/L and time
for thickness = 0.75 in
Initial carbon temperature = 900 F.

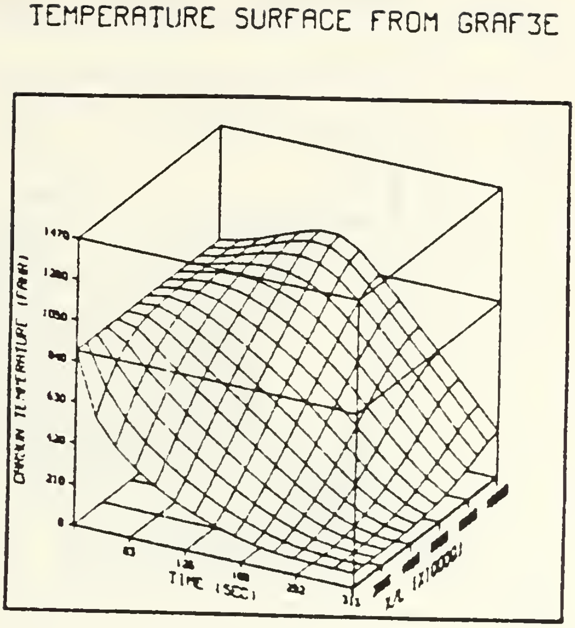


Figure 3.14 Temperature vs X/L and time
for thickness = 0.75 in
Initial carbon temperature = 890 F.

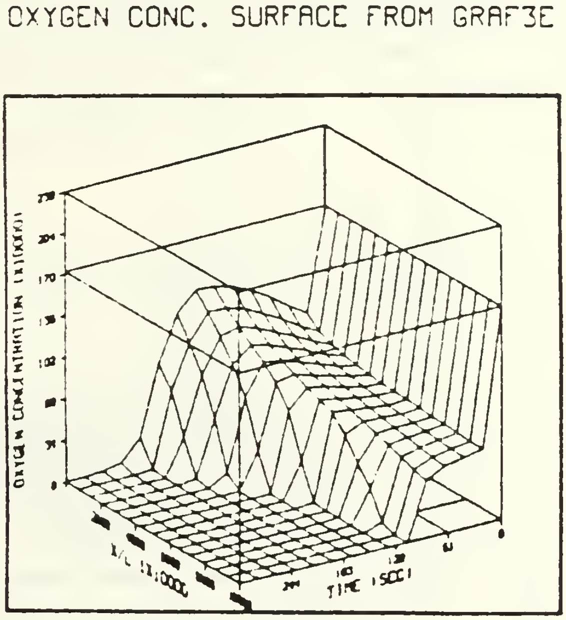


Figure 3.15 Oxygen concentration vs X/L and time
for thickness = 0.75 in
Initial carbon temperature = 900 F.

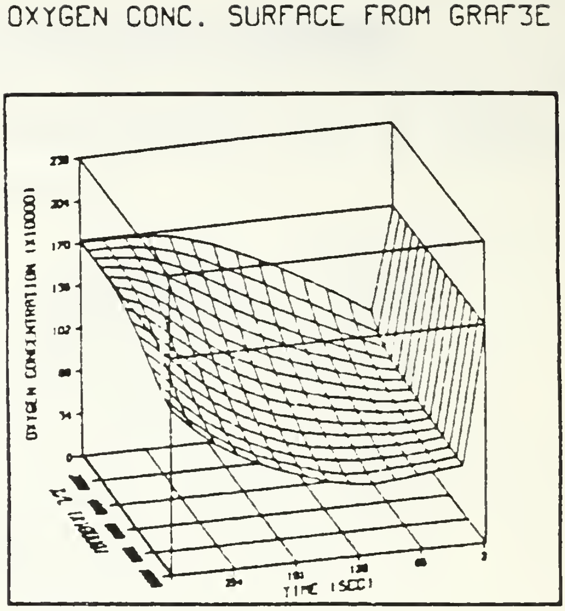


Figure 3.16 Oxygen concentration vs X/L and time
for thickness = 0.75 in
Initial carbon temperature = 890 F.

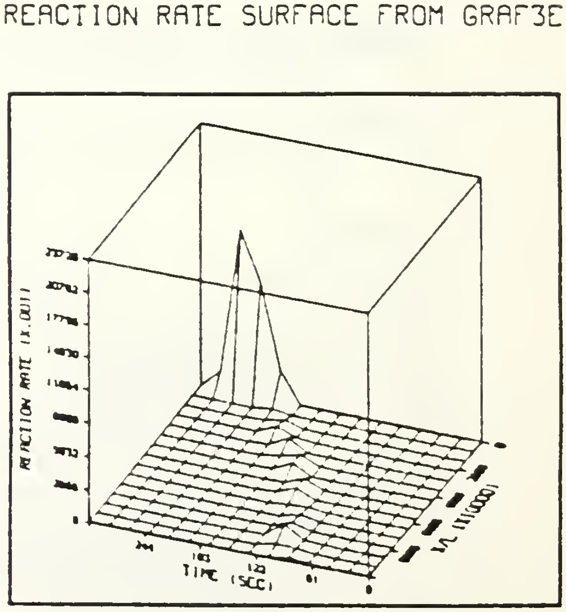


Figure 3.17 Reaction rate vs X/L and time
for thickness = 0.75 in
Initial carbon temperature = 900 F.

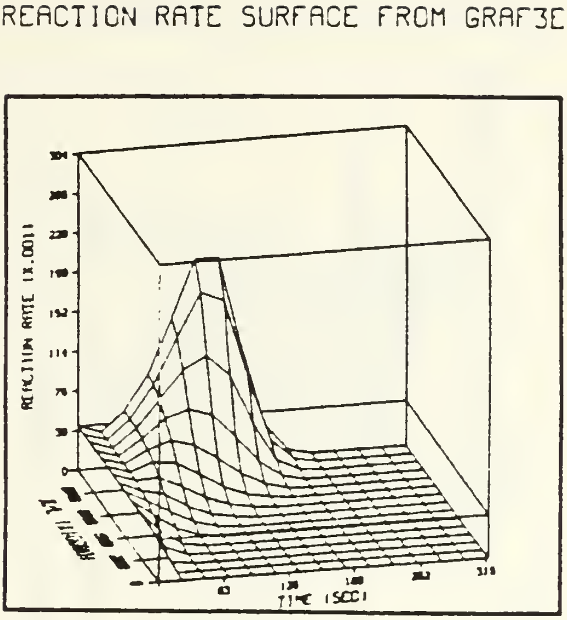


Figure 3.18 Reaction rate vs X/L and time
for thickness = 0.75 in
Initial carbon temperature = 890 F.

4. CASE III-4 Thickness = 1.00 inches

The program was run with several values of initial uniform graphite temperature . The temperatures bounding combustion and extinction are:

for combustion Tc = 850 F
for extinction Te = 840 F

The variable parameters of this case attain maximum and minimum values as given in Table VIII .

In this case, the graphical results for carbon temperature, oxygen concentration and reaction rate are shown in Figures 3.19 to 3.24 .

TABLE VII

VARIED PARAMETERS DURING THE PROCESS FOR THICKNESS = 0.75 INCHES

parameters	extinction		combustion	
	maximun	minimun	maximun	minimun
permeability (ft.sq)(10^{-10})	1.733	1.617	1.863	1.617
pressure (lb/ft.sq)	2117	2066	2117	2066
pressure gradient (lb/ft.cu)	-331	-1309	-236	-1257
pore velocity (ft/hr)	2301	906	2085	633
Reynolds number	0.1684	0.0623	0.1116	0.0416
convection coefficient	28.60	19.36	26.99	16.27

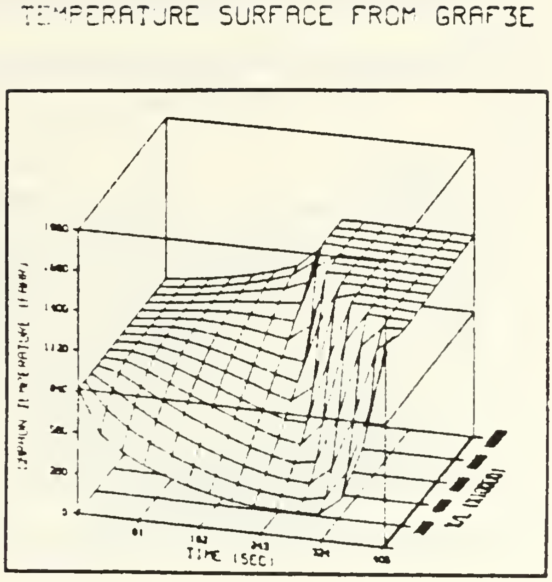


Figure 3.19 Temperature vs X/L and time
for thickness = 1.00 in
Initial carbon temperature = 850 F.

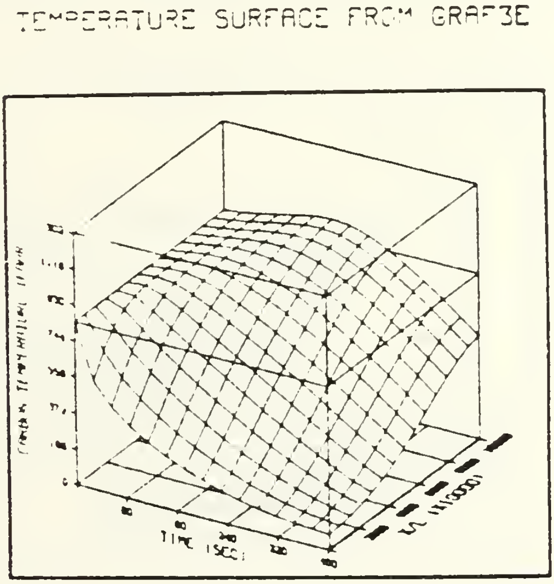


Figure 3.20 Temperature vs X/L and time
for thickness = 1.00 in
Initial carbon temperature = 840 F.

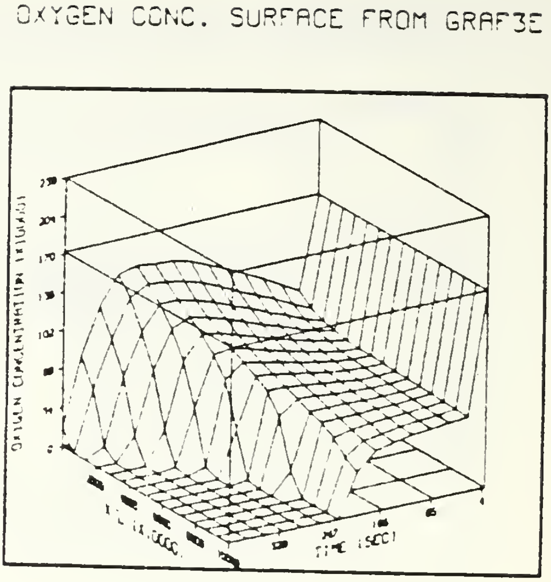


Figure 3.21 Oxygen concentration vs X/L and time for thickness = 1.00 in
Initial carbon temperature = 850 F.

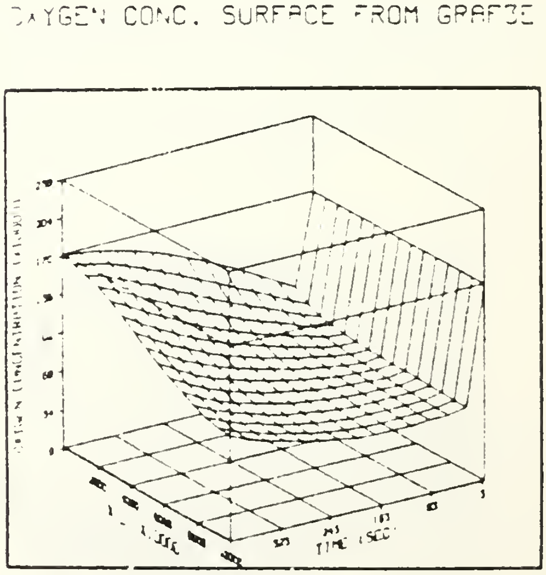
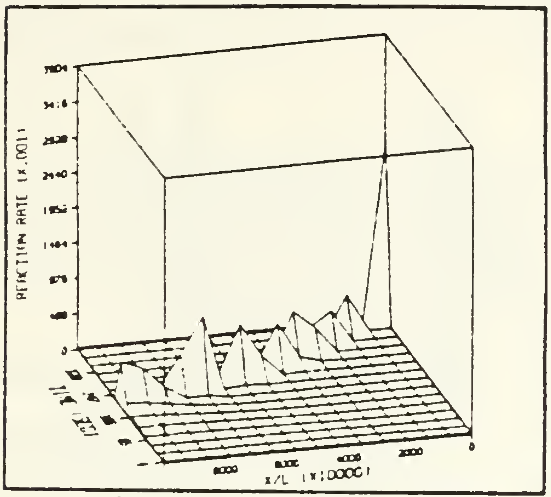
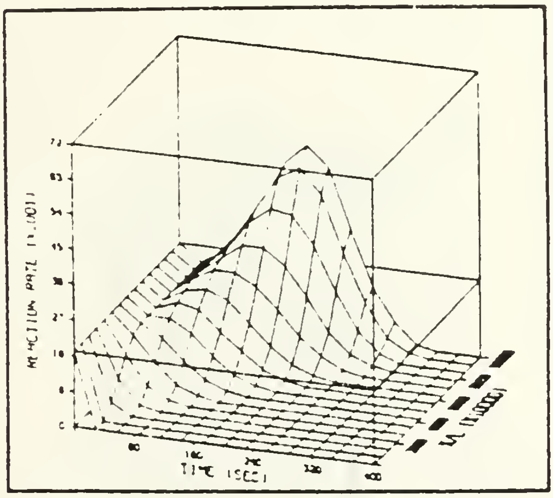


Figure 3.22 Oxygen concentration vs X/L and time for thickness = 1.00 in
Initial carbon temperature = 840 F.



REACTION RATE SURFACE FROM GRAF3E

Figure 3.23 Reaction rate vs X/L and time for thickness = 1.00 in Initial carbon temperature = 850 F.



REACTION RATE SURFACE FROM GRAF3E

Figure 3.24 Reaction rate vs X/L and time for thickness = 1.00 in Initial carbon temperature = 840 F.

TABLE VIII

VARIED PARAMETERS DURING THE PROCESS FOR THICKNESS = 1.00 INCHES

parameters	extinction		combustion	
	maximun	minimun	maximun	minimun
permeability (ft.sq)(10^{-10})	1.911	1.617	1.874	1.617
pressure (lb/ft.sq)	2117	2067	2117	2066
pressure gradient (lb/ft.cu)	-360	-1289	-260	-1257
pore velocity (ft/hr)	1835	715	1535	686
Reynolds number	0.2313	0.0531	0.1108	0.0518
convection coefficient	28.04	17.27	24.09	16.99

5. CASE III-5 Thickness = 2.00 inches

The combustion and extinction process, in this case, are characterized by the following uniform initial graphite temperatures:

for combustion Tc = 760 F
for extinction Te = 750 F

The graphite temperature and other parameters varied during these processes . The variation of these parameters characterize the system. The maximum and minimum values of these parameters are in Table IX .

The graphical results for carbon temperature, oxygen concentration and reaction rate are shown in Figures 3.25 to 3.30 .

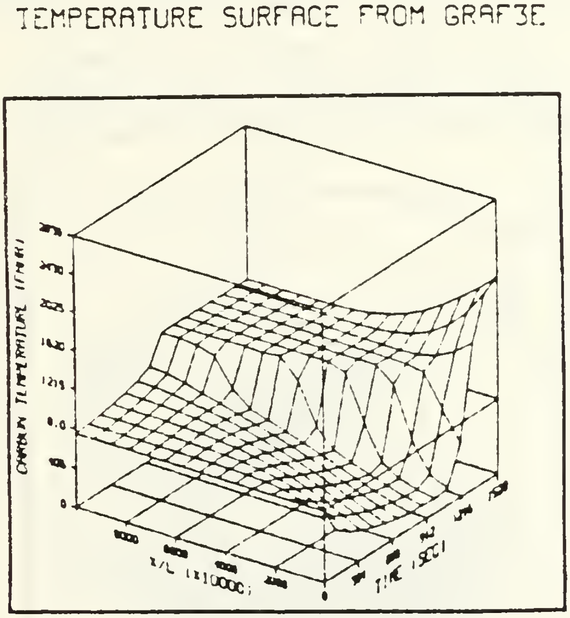


Figure 3.25 Temperature vs X/L and time
for thickness = 2.00 in
Initial carbon temperature = 760 F.

TEMPERATURE SURFACE FROM GRAF3E

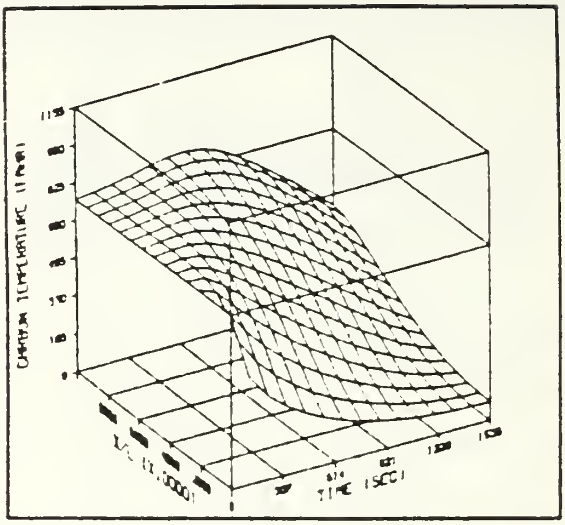


Figure 3.26 Temperature vs X/L and time
for thickness = 2.00 in
Initial carbon temperature = 750 F.

OXYGEN CONC. SURFACE FROM GRAF3E

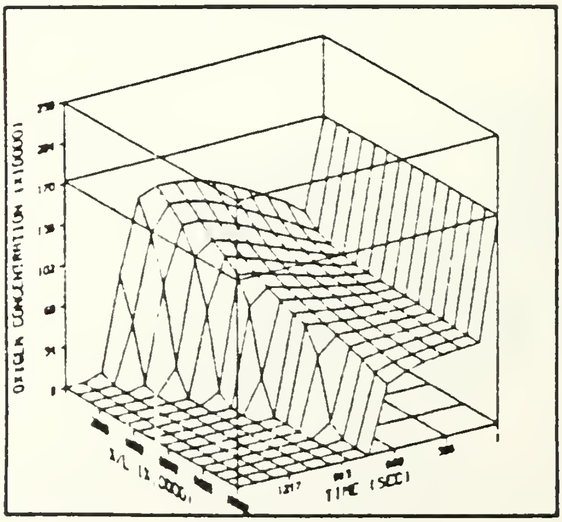


Figure 3.27 Oxygen concentration vs X/L and time
for thickness = 2.00 in
Initial carbon temperature = 760 F.

OXYGEN CONC. SURFACE FROM GRAF3E

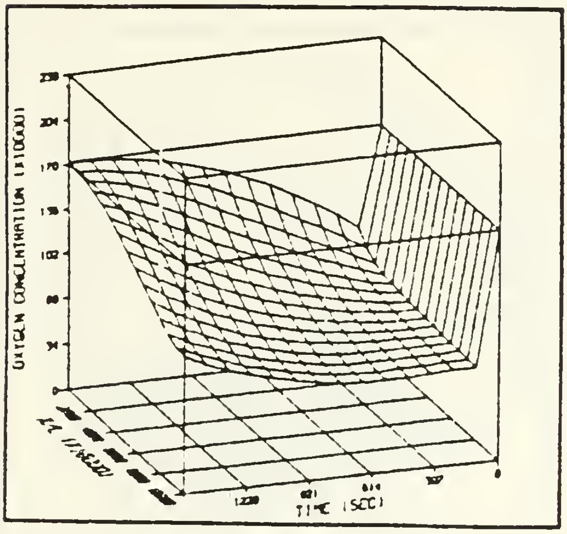


Figure 3.28 Oxygen concentration vs X/L and time
for thickness = 2.00 in
Initial carbon temperature = 750 F.

REACTION RATE SURFACE FROM GRAF4BE

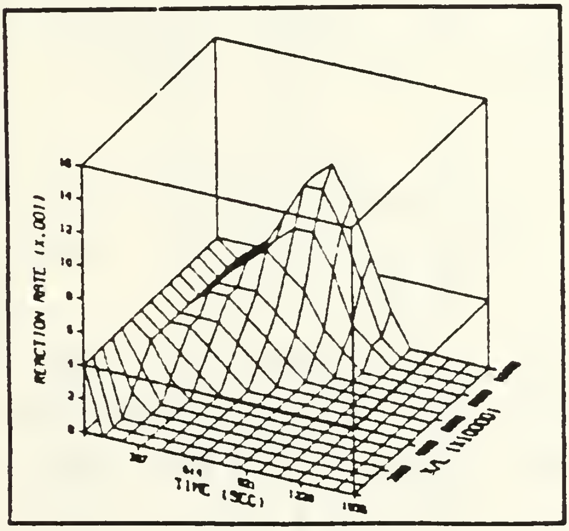


Figure 3.29 Reaction rate vs X/L and time
for thickness = 2.00 in
Initial carbon temperature = 760 F.

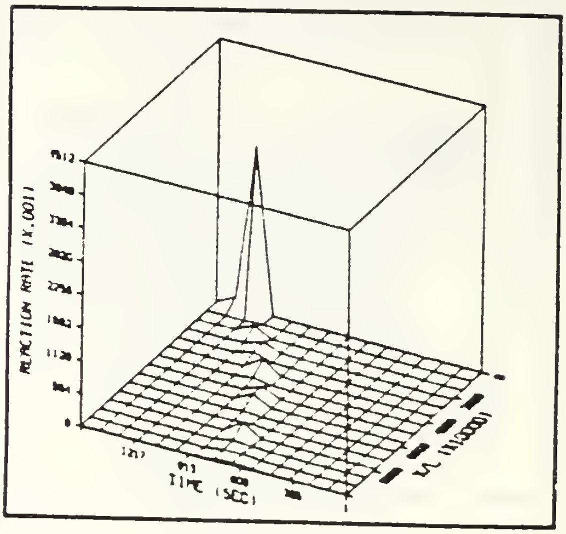

REACTION RATE SURFACE FROM GRAF3E

Figure 3.30 Reaction rate vs X/L and time
for thickness = 2.00 in
Initial carbon temperature = 750 F.

6. CASE III-6 Thickness = 4.00 inches

The minimum value of the initial graphite temperature to start combustion of the porous medium and the maximum value of the initial graphite temperature that results in extinction for this case are:

for combustion Tc = 690 F
for extinction Te = 680 F

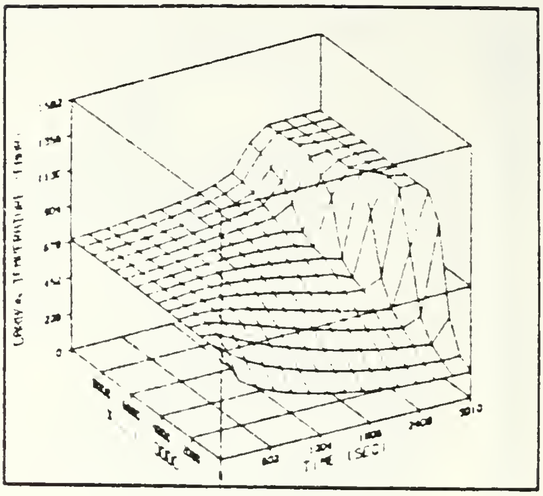
Other variable parameters of this case are shown in Table X . The values of these parameters are characteristic of the combustion and extinction processes for this value of thickness.

In this case, the graphical results show the behavior of carbon temperature , oxygen concentration and reaction rate in Figures 3.31 to 3.36

TABLE IX

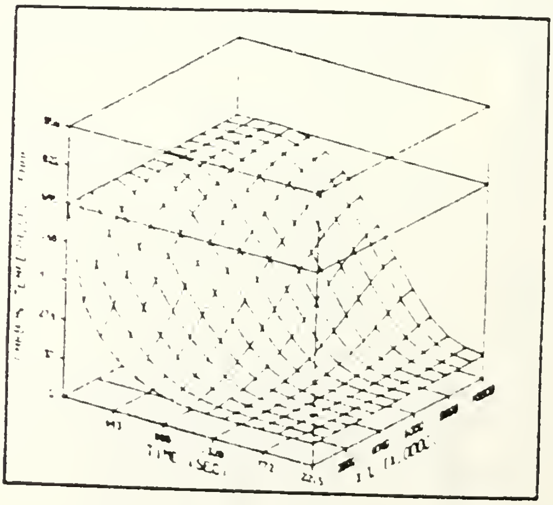
VARIED PARAMETERS DURING THE PROCESS FOR THICKNESS = 2.00 INCHES

parameters	extinction		combustion	
	maximun	minimun	maximun	minimun
permeability (ft.sq)(10^{-10})	1.748	1.617	1.822	1.617
pressure (lb/ft.sq)	2117	2066	2117	2067
pressure gradient (lb/ft.cu)	-136	-482	-88	-525
pore velocity (ft/hr)	1004	381	899	346
Reynolds number	0.1025	0.0303	0.0561	0.0206
convection coefficient	19.39	12.75	17.54	12.66



TEMPERATURE SURFACE FROM GRAF3E

Figure 3.31 Temperature vs X/L and time
for thickness = 4.00 in
Initial carbon temperature = 690 F.



TEMPERATURE SURFACE FROM GRAF3E

Figure 3.32 Temperature vs X/L and time
for thickness = 4.00 in
Initial carbon temperature = 680 F.

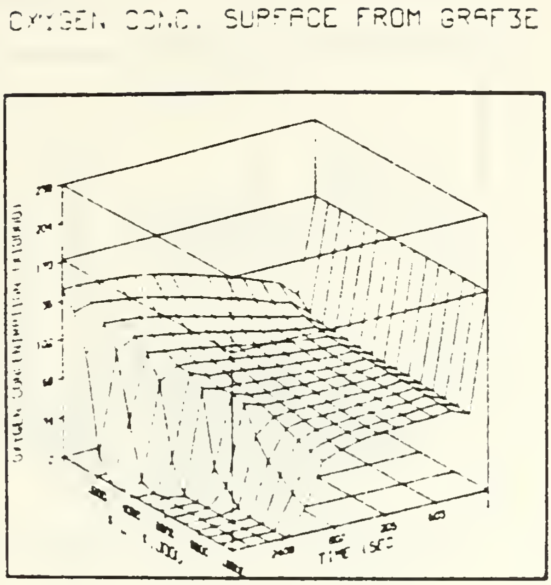


Figure 3.33 Oxygen concentration vs X/L and time
for thickness = 4.00 in
Initial carbon temperature = 690 F.

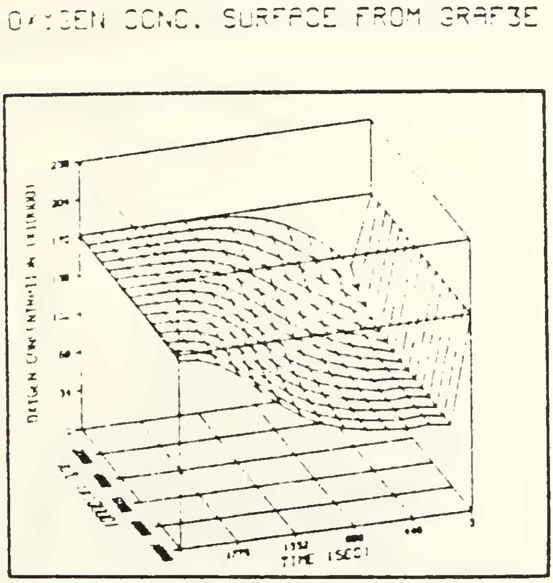


Figure 3.34 Oxygen concentration vs X/L and time
for thickness = 4.00 in
Initial carbon temperature = 680 F.

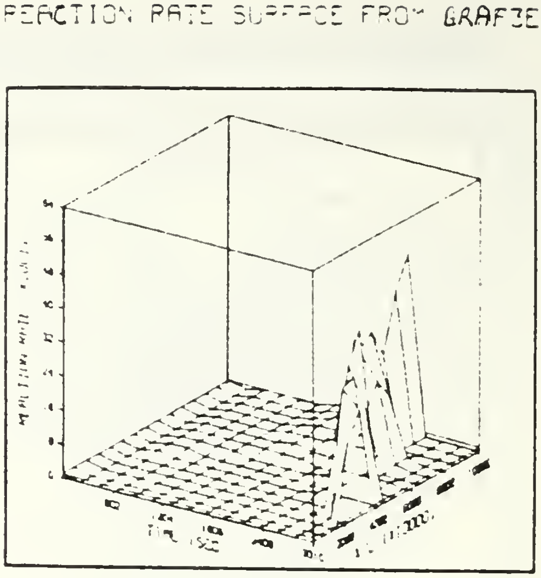


Figure 3.35 Reaction rate vs X/L and time
for thickness = 4.00 in
Initial carbon temperature = 690 F.

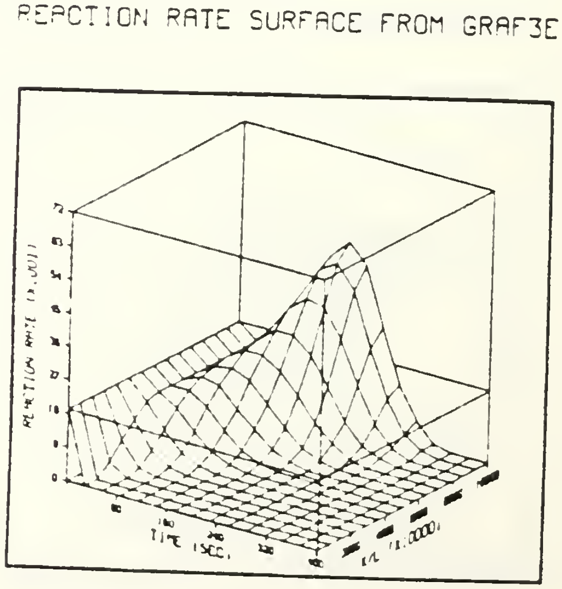


Figure 3.36 Reaction rate vs X/L and time
for thickness = 4.00 in
Initial carbon temperature = 680 F.

TABLE X

VARIED PARAMETERS DURING THE PROCESS FOR THICKNESS = 4.00 INCHES

parameters	extinction		combustion	
	maximun	minimun	maximun	minimun
permeability (ft.sq)(10^{-10})	1.659	1.617	1.710	1.617
pressure (lb/ft.sq)	2117	2067	2117	2066
pressure gradient (lb/ft.cu)	-166	-241	-49	-242
pore velocity (ft/hr)	444	199	410	136
Reynolds number	0.0371	0.0174	0.0289	0.0124
convection coefficient	12.89	9.30	12.27	7.86

7. CASE III-7 Thickness = 6.00 inches

Below is given the initial uniform carbon temperature for combustion and extinction:

for combustion Tc = 650 seconds
for extinction Te = 640 seconds

The variable parameters for this case are given in Table XI

The Figures 3.37 to 3.42 show the development of carbon temperature, oxygen concentration and reaction rate at each position during the combustion and extinction processes.

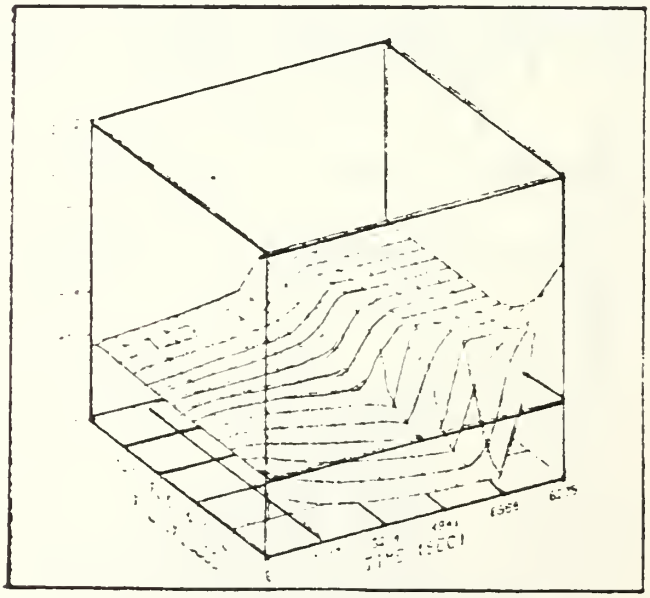


Figure 3.37 Temperature vs X/L and time
for thickness = 6.00 in
Initial carbon temperature = 650 F.

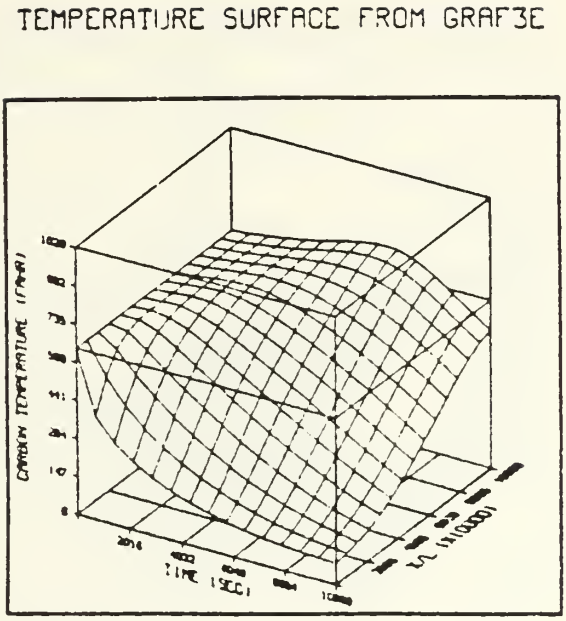


Figure 3.38 Temperature vs X/L and time for thickness = 6.00 in Initial carbon temperature = 640 F.

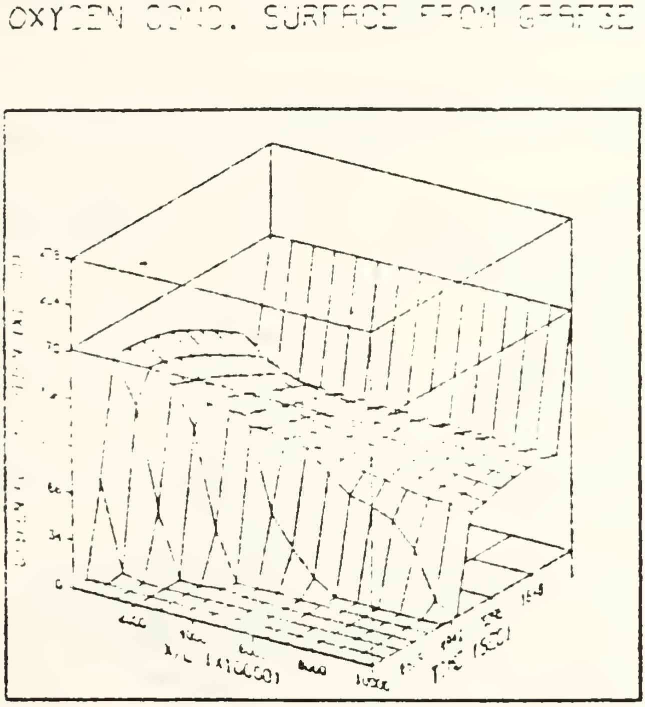


Figure 3.39 Oxygen concentration vs X/L and time for thickness = 6.00 in Initial carbon temperature = 650 F.

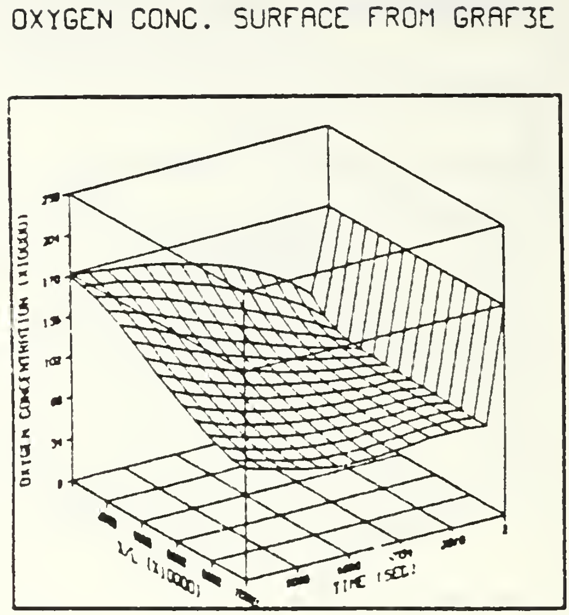


Figure 3.40 Oxygen concentration vs X/L and time
for thickness = 6.00 in
Initial carbon temperature = 640 F.

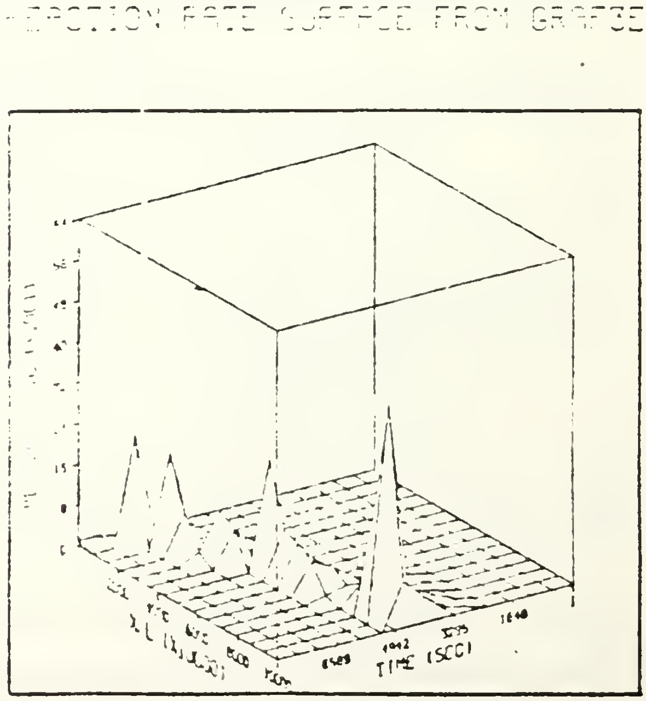
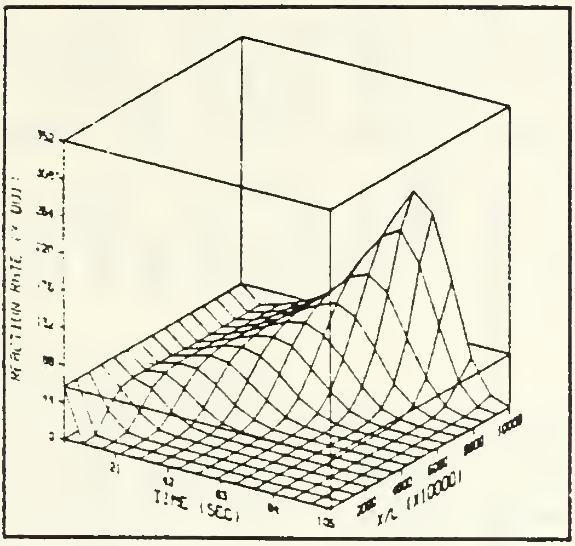


Figure 3.41 Reaction rate vs X/L and time
for thickness = 6.00 in
Initial carbon temperature = 650 F.



REACTION RATE SURFACE FROM GRAF3E

Figure 3.42 Reaction rate vs X/L and time
for thickness = 6.00 in
Initial carbon temperature = 640 F.

D. SUMMARY

Here, some observations are made about the effects of thickness on the combustion process.

1. Power Relation

For each case a pair of values (thickness, combustion temperature) was obtained. Four plots of this data are shown in Figures 3.43 to 3.46 .

Figures 3.43 and 3.44 show thickness versus combustion temperature , and Figures 3.45 and 3.46 show thickness versus the time it takes for the oxygen concentration at X/L = 1. to reach.

It is observed that the relation between thickness and combustion temperature , figure 3.43 has a form which approximates an exponentially decreasing function.

The log-log plot (Figure 3.44) is close to a linear form, which yields the approximate power relation.

The temperature is in degrees fahrenheit and thickness is in inches .

TABLE XI

VARIED PARAMETERS DURING THE PROCESS FOR THICKNESS = 6.00 INCHES

parameters	extinction		combustion	
	maximun	minimun	maximun	minimun
permeability (ft.sq)(10^{-10})	1.657	1.617	1.717	1.617
pressure (lb/ft.sq)	2117	2067	2117	2066
pressure gradient (lb/ft.cu)	-48.8	-160.8	-33.4	-149.8
pore velocity (ft/hr)	325	138	292	99
Reynolds number	0.0318	0.0126	0.0201	0.0056
convection coefficient	11.14	7.75	10.37	6.41

$$T = 850\ L^{-0.16554} \tag{3.1}$$

A comparison of the computer program's results and the formula's results are given in Table III. The maximum difference between the analytical results and the power equation results is less than 3 percent over the range of thickness between 0.25 and 6.00 inches .

This shows that the formula is a good approximation for these cases.

2. Combustion Start Time

During the initial phase of the combustion process, the oxygen concentration at all points of the porous medium continuously decreases to zero. for all cases, the point of the porous medium that first reached zero was X/L = 1. The time it taken for that the oxygen concentration at X/L = 1. to reach zero is important because it is related to the time that combustion starts.

Figure 3.45 , shows that this time does not increase linearly with the thickness. The log-log plot of these values, Figure 3.46 , shows that this log-log plot is approximately a straight line.

The equation for this line is:

$$T^{*} = 226.8\ L^{1.683} \tag{3.2}$$

This equation can be used to give an estimate for the time it takes for combustion to start.

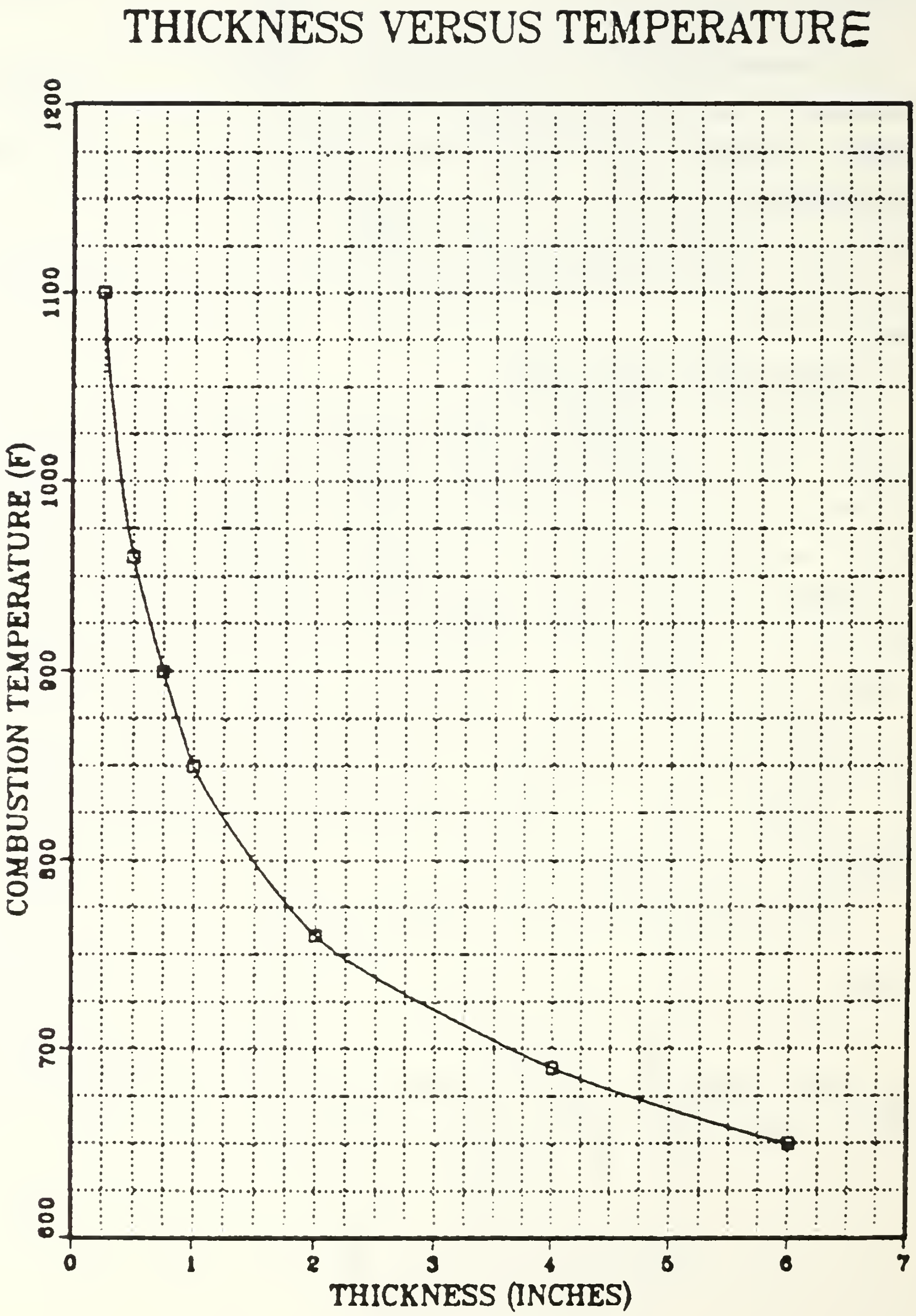


Figure 3.43 Thickness versus combustion temperature Retangular plot.

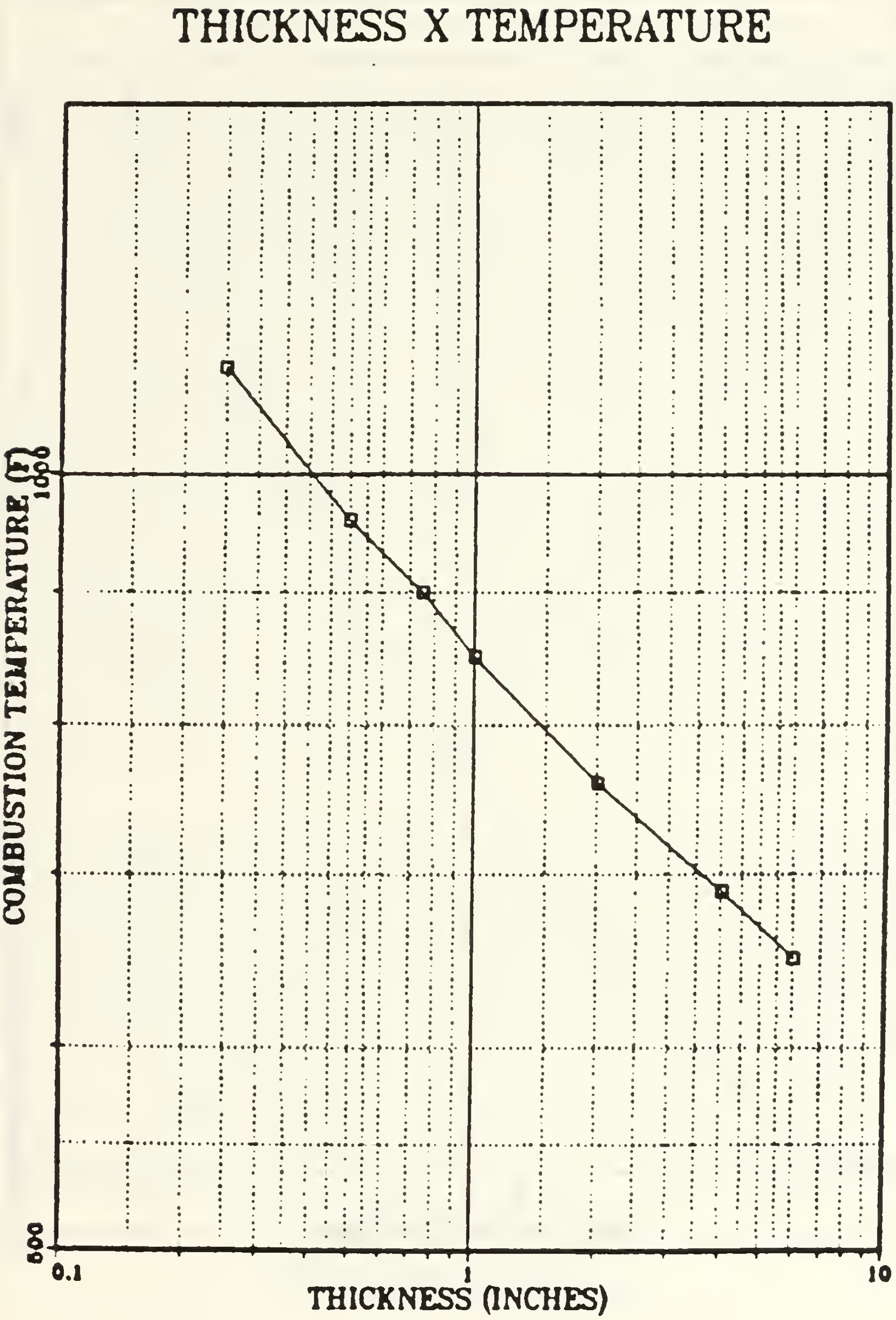


Figure 3.44 Thickness versus combustion temperature Log-log plot.

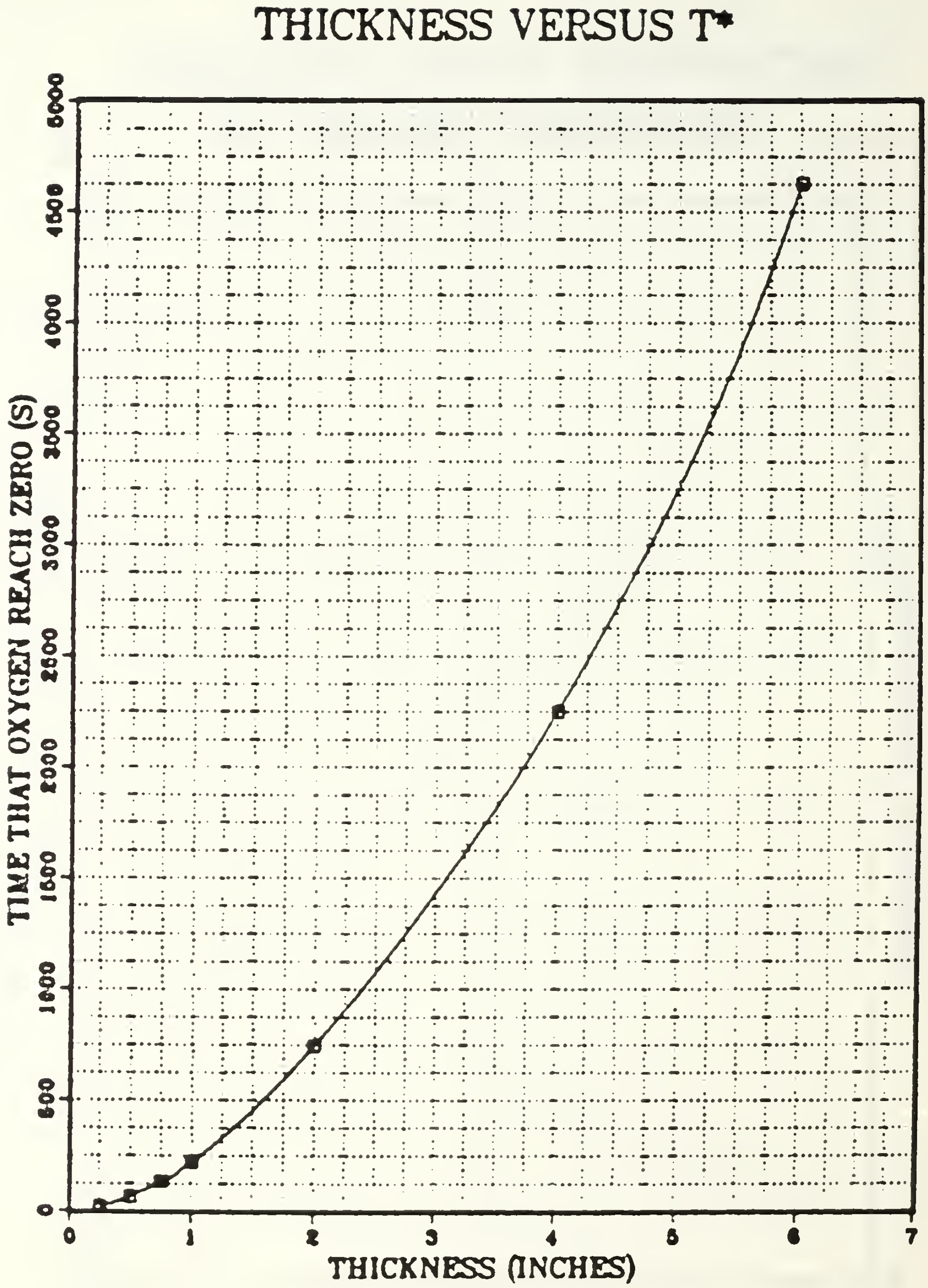


Figure 3.45 Thickness vs time for oxygen concentration at X/L = 1. to reach zero Retangular plot.

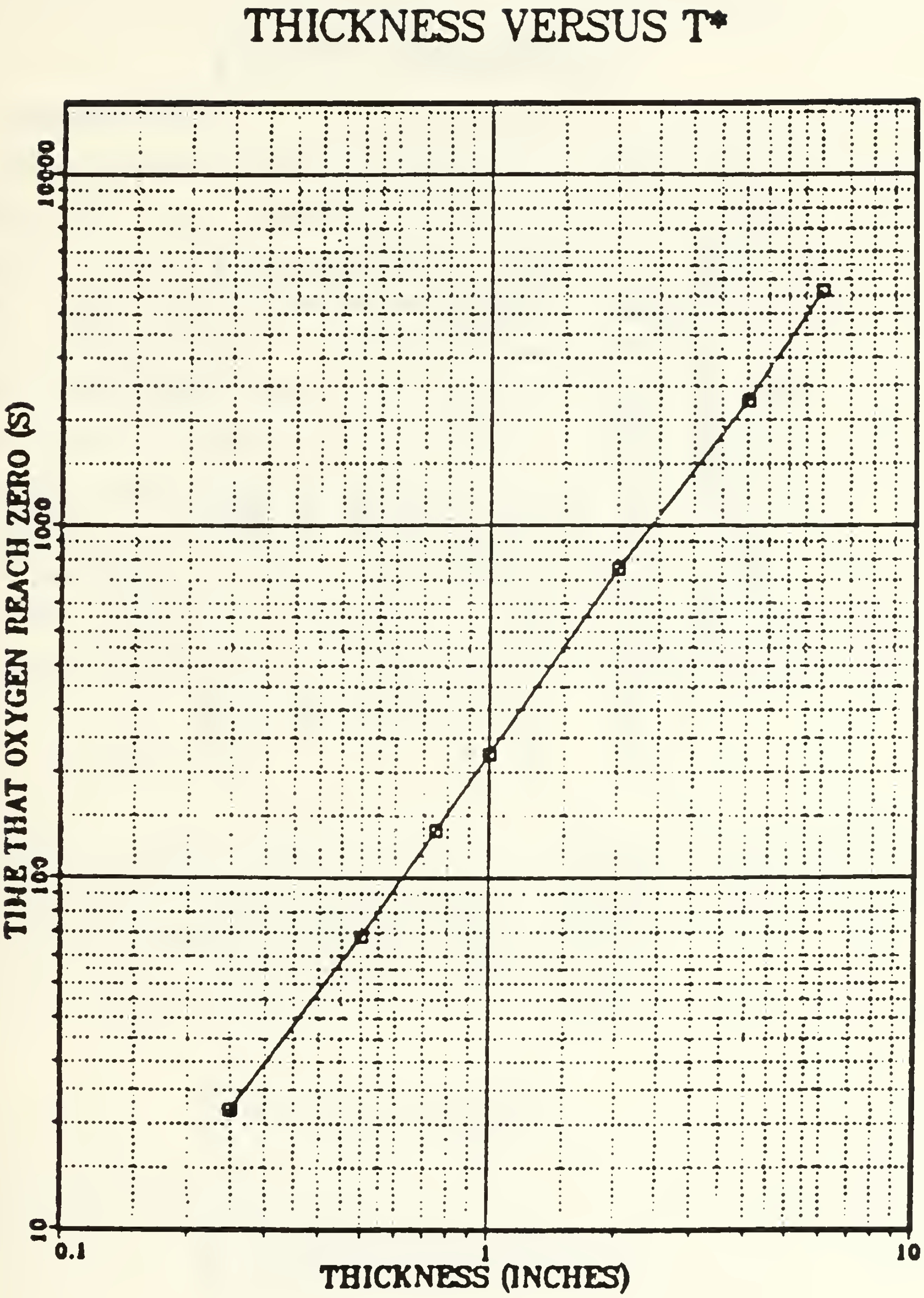


Figure 3.46 Thickness vs time for oxygen concentration reach zero log-log plot.

TABLE XII

RESULTS FOR ALL THICKNESS CASES

cases	L(in)	extinction temperature (F)	combustion temperature (F)		% error	t* (s)
			program	power relation		
III-1	0.25	1090	1100	1090	2.8	22
III-2	0.50	950	960	950	0.7	68
III-3	0.75	890	900	890	0.9	136
III-4	1.00	840	850	840	0.0	225
III-5	2.00	750	760	750	0.3	748
III-6	4.00	680	690	680	2.1	2253
III-7	6.00	640	650	640	2.8	4626

IV. PERMEABILITY

A. INTRODUCTION

The permeability or hydraulic conductivity of a porous medium is the capacity of air flow through the porous medium. The air provides the oxygen for combustion . On the other hand , air flow provides for convective heat transfer within the medium . Thus air flow provides for heat generation from combustion , as well as heat transfer by convection . The interaction of these two mechanisms determines whether combustion or extinction will occur . If the heat generation of combustion is greater than the heat transfer of convection , then combustion will occur . If the heat transfer mechanism dominates , then extinction will occur . The equation used for permeability in the program is :

$$m = 0.2\ p^3 / z^2 \qquad (4.1)$$

Where m is the permeability , p is the porosity and z is the specific internal area . The expressions for porosity and specific internal area are :

$$p = 1 - \pi / 6(d/D)^3 \qquad (4.2)$$

$$z = 1/2\ \pi\ (d/D^2) \qquad (4.3)$$

$$z = 1/2\ \pi\ (d^2/D^3) \qquad (4.4)$$

The equation 4.3 is for spherical particles and equation 4.4 is for cylindrical particles . Equation 4.1 is the Kozeny equation for permeability of porous medium . This equation fails for highly porous fibrous media .

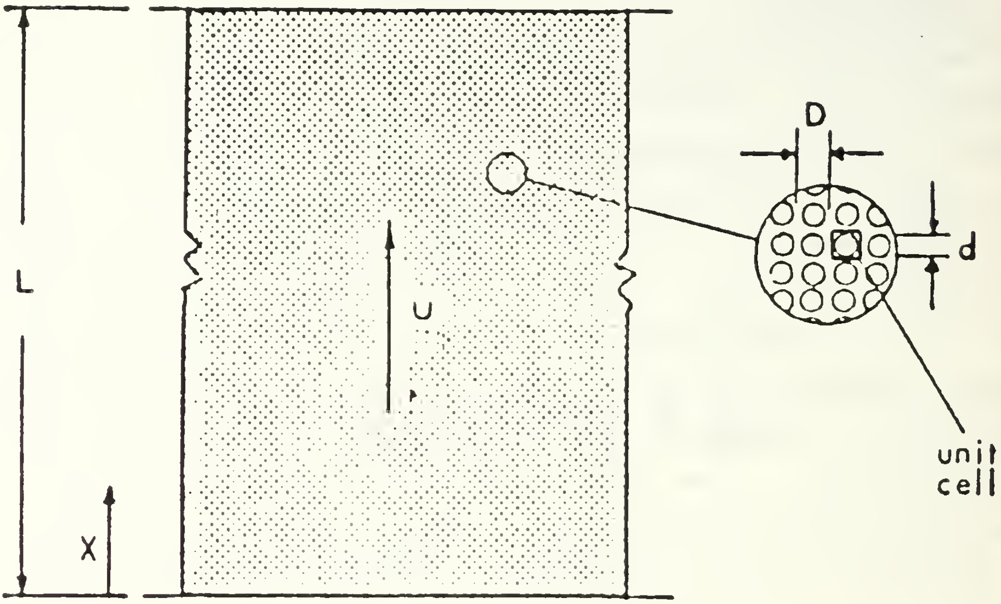


Figure 4.1 Geometry of a typical cell.

This equation fails for highly porous fibrous medias .

The tortuosity ,τ , is the ratio of the length of the flow path for a fluid particle to the straight line distance. The tortuosity depends on the ratio d/D .In this program tortuosity was assumed to have a constant value of 1.4 .

Normally the interior geometry of a porous medium can be inregular and complex . In such cases the internal structure is difficult to discribe analytically . The program used in this investigation models the porous medium as consisting of cylindrical fibers or spherical particles in a regular periodic geometry as shown in Figures 4.1 .

During the combustion process carbon is being continuously consumed and as a result, the internal geometry is changing. The medium becomes more porous as the carbon decreases. Therefore, all properties which depend upon fiber or particle diameter are functions of time and position. The model used in the program assumed that the carbon matrix remains rigid as the particles diameter decreases , and thus , the porosity increases with combustion .

B. PROCEDURE

To study the effects of permeability on combustion , all parameters of the program were maintained constant , except the permeability . In order to change the permeability and keep the porosity constant , it is necessary to keep the (d/D) ratio constant as seen in the equations 4.5 and 4.6 . This is accomplished by setting d/D equal to α . Then the numerator of equation 4.1 remains constant , however the denominator changes because d $=\alpha$ D and Z gives :

$$Z = 1/2\ \pi(\alpha\ d/D^2) = \text{constant} / D \qquad (4.5)$$

$$Z = 1/2\ \pi(\alpha^2\ d^2/D^3) = \text{constant} / D \qquad (4.6)$$

Thus , the dimensions of d and D were changed proportionally so that the initial ratio (d/D) remained constant in all cases . Thus the porosity remained constant while the permeability was different for each case .

The cases studied in this section are :

CASE IV-1 PERMEABILITY = 0.00015 ft^2 (d=D=0.0025 in)
CASE IV-2 PERMEABILITY = 0.00058 ft^2 (d=D=0.0050 in)
CASE IV-3 PERMEABILITY = 0.00233 ft^2 (d=D=0.0100 in)
CASE IV-4 PERMEABILITY = 0.00933 ft^2 (d=D=0.0200 in)

For each values of permeability the program was run with different uniform carbon temperatures for all points (X/L) . This procedure was repeated until we obtaind the minimum temperature that results in combustion . This temperature is called the combustion temperature (T_c) . Extinction occurs at temperatures below T_c .

$$T_c = T_e + \delta \tag{4.7}$$

In this section this difference (δ) was chosen equal at 10 F then :

$$T_c = T_e + 10 \quad (F) \tag{4.8}$$

C. RESULTS

For each case , the program provided the values of the carbon and air temperatures inside the porous medium , as well as other parameters which varied during the combustion process .

1. CASE IV-1 Permeability = 0.00015 ft^2 (d=D=0.0025 in)

For this value of permeability , the maximum carbon temperature that does not result in combustion (extinction temperature) and the minimum temperature that results in combustion (combustion temperature) are :

for combustion $T_c = 760$ F
for extinction $T_e = 750$ F

The graphical results are shown in Figures 4.2 to 4.7 . These graphical surfaces show the carbon temperature , oxygen concentration and reaction rate at each position and time . The form of these surfaces shows the different behavior of these three parameters during the extinction and combustion processes.

TEMPERATURE SURFACE FROM GRAF3E

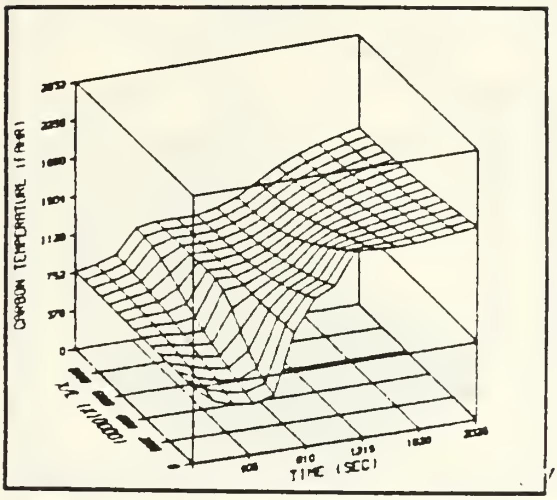


Figure 4.2 Temperature vs X/L and time
for permeability = 0.00015 ft^2
initial carbon temperatiure = 760 F.

TEMPERATURE SURFACE FROM GRAF3E

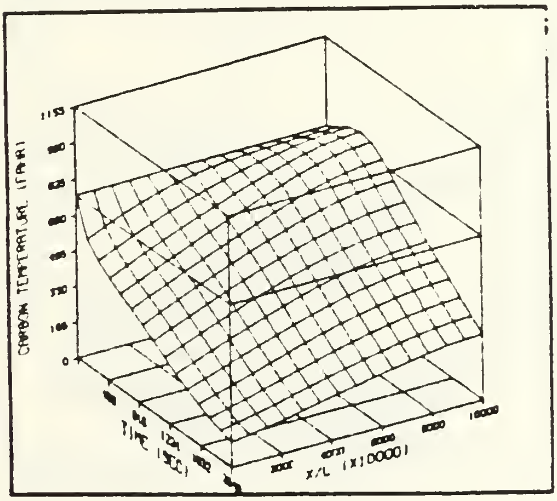


Figure 4.3 Temperature vs X/L and time
for permeability = 0.00015 ft^2
initial carbon temperatiure = 750 F.

OXYGEN CONC. SURFACE FROM GRAF3E

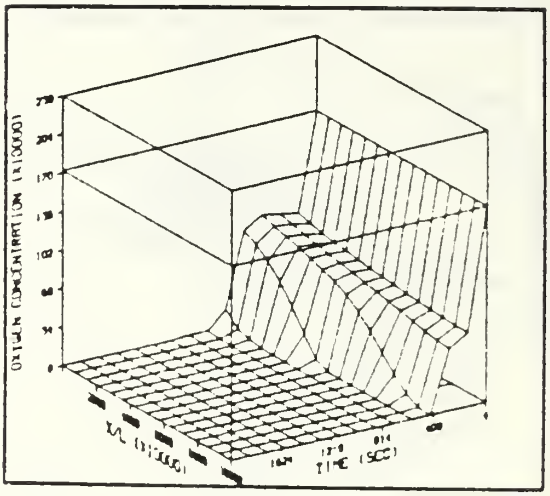


Figure 4.4 Oxygen concentration vs X/L and time for permeability = 0.00015 ft^2 initial carbon temperatiure = 760 F.

OXYGEN CONC. SURFACE FROM GRAF3E

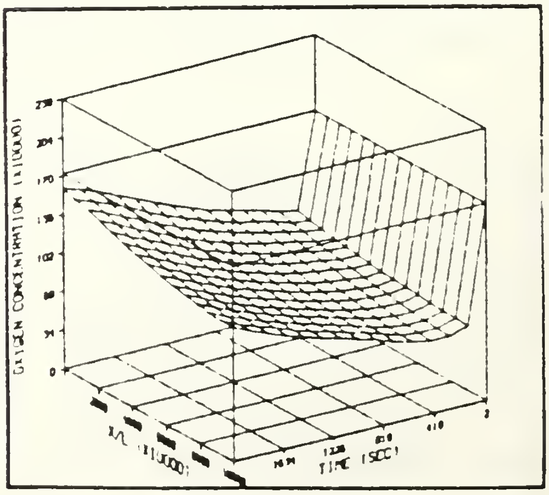


Figure 4.5 Oxygen comcentration vs X/L and time for permeability = 0.00015 ft^2 initial carbon temperatiure = 750 F.

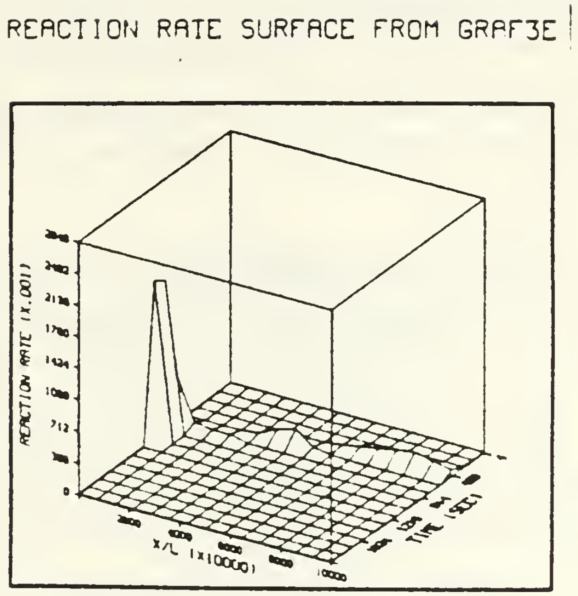


Figure 4.6 Reaction rate vs X/L and time for permeability = 0.00015 ft^2 initial carbon temperatiure = 760 F.

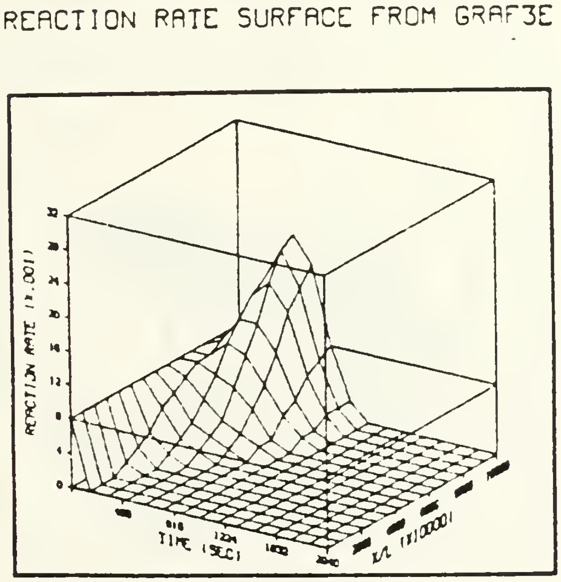


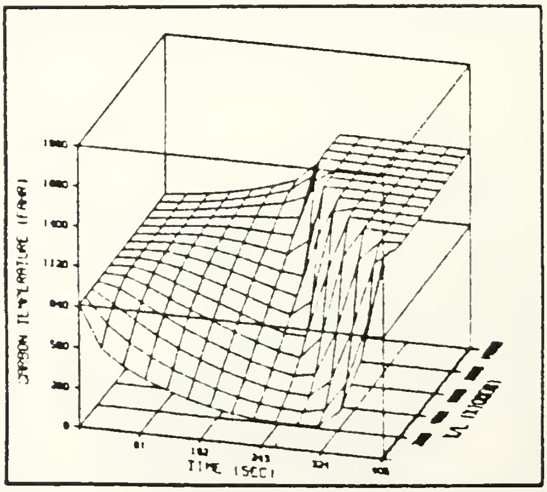
Figure 4.7 Reaction rate vs X/L and time for permeability = 0.00015 ft^2 initial carbon temperatiure = 750 F.

2. CASE IV-2 Permeability = 0.00058 ft^2 (d=D=0.0050 in)

Here the value of permeability is 0.00058 ft^2 which results from a pore diameter of 0.0050 in . For this case the combustion and extinction temperatures are :

for combustion T_c = 850 0 F
for extinction T_e = 840 0 F

From the numerical output of the program , three graphical surface s were created ; the carbon temperature , oxygen concentration and reaction rate as functions of time and position . These surfaces provide information of the development of these three dependent variables during the combustion and extinction process . These surfaces are shown on Figures 4.8 to 4.13 .



TEMPERATURE SURFACE FROM GRAF3E

Figure 4.8 Temperature vs X/L and time
for permeability = 0.00058 ft^2
initial carbon temperatiure = 850 F.

TEMPERATURE SURFACE FROM GRAF3E

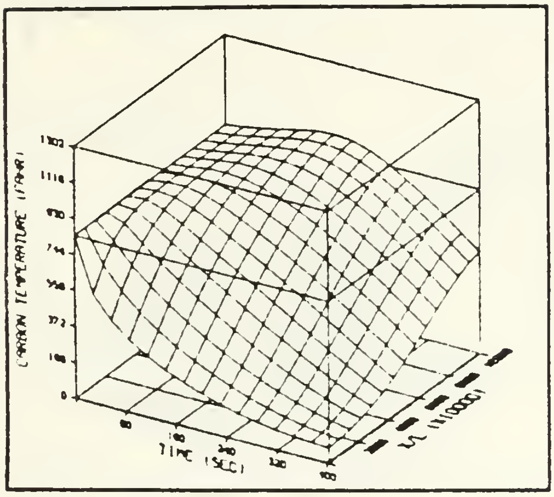


Figure 4.9 Temperature vs X/L and time
for permeability = 0.00058 ft^2
initial carbon temperatiure = 840 F.

OXYGEN CONC. SURFACE FROM GRAF3E

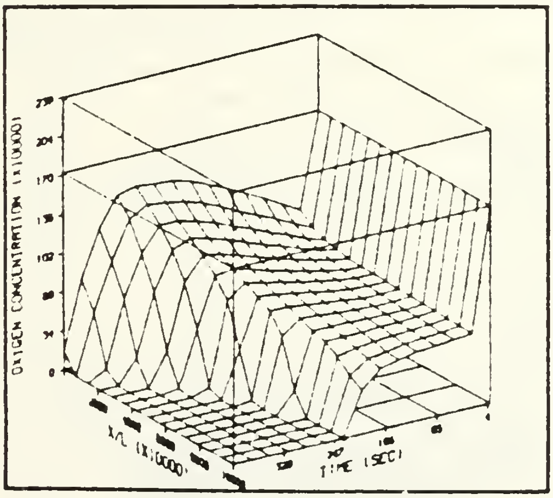


Figure 4.10 Oxygen concentration vs X/L and time
for permeability = 0.00058 ft^2
initial carbon temperatiure = 850 F.

OXYGEN CONC. SURFACE FROM GRAF3E

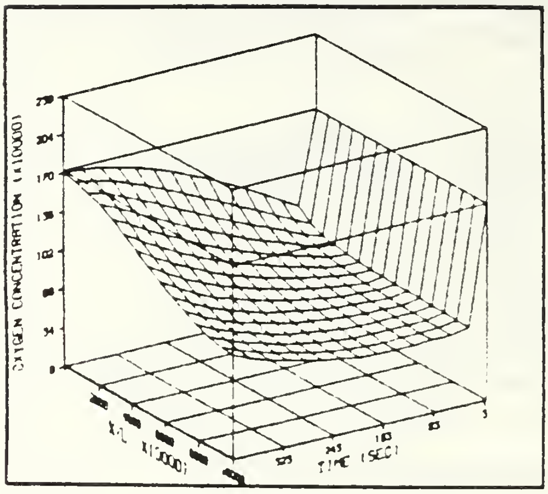


Figure 4.11 Oxygen comcentration vs X/L and time
for permeability = 0.00058 ft^2
initial carbon temperatiure = 840 F.

REACTION RATE SURFACE FROM GRAF3E

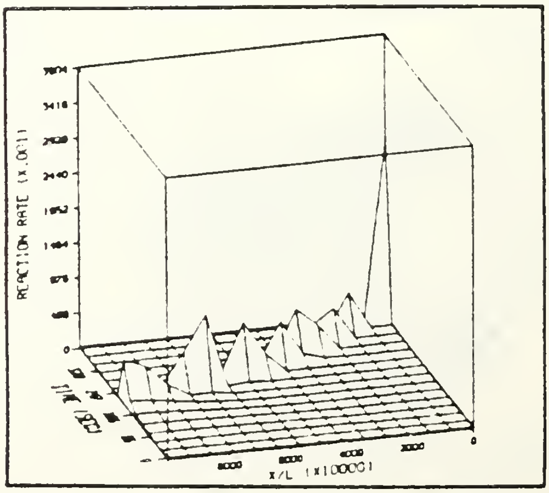


Figure 4.12 Reaction rate vs X/L and time
for permeability = 0.00058 ft^2
initial carbon temperatiure = 850 F.

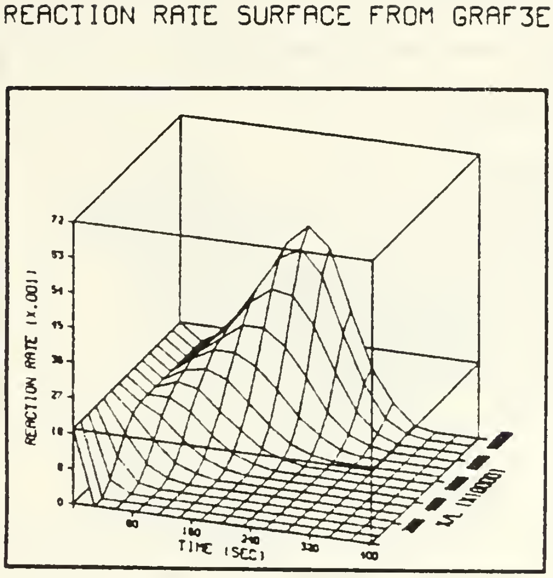


Figure 4.13 Reaction rate vs X/L and time for permeability = 0.00058 ft^2 initial carbon temperatiure = 840 F.

3. CASE IV-3 Permeability = 0.00233 ft^2 (d=D=0.0100 in)

For this case the initial permeability is 0.00233 ft^2 . With this value of permeability the combustion and extinction temperatures are :

for combustion T_c = 980 0.F
for extinction T_e = 970 0.F

The variation of the dependent variables during the combustion and extinction cases is shown by a numerical output of the program . These results are also shown in three graphical surfaces ; carbon temperature , oxygen concentration and reaction rate on each position (X/L) and time . These graphical results are shown in Figures 4.14 to 4.19

TEMPERATURE SURFACE FROM GRAF3E

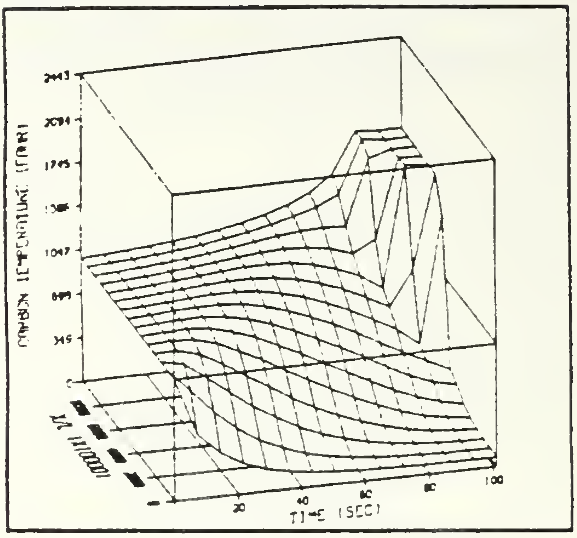


Figure 4.14 Temperature vs X/L and time for permeability = 0.00233 ft^2 initial carbon temperatiure = 980 F.

TEMPERATURE SURFACE FROM GRAF3E

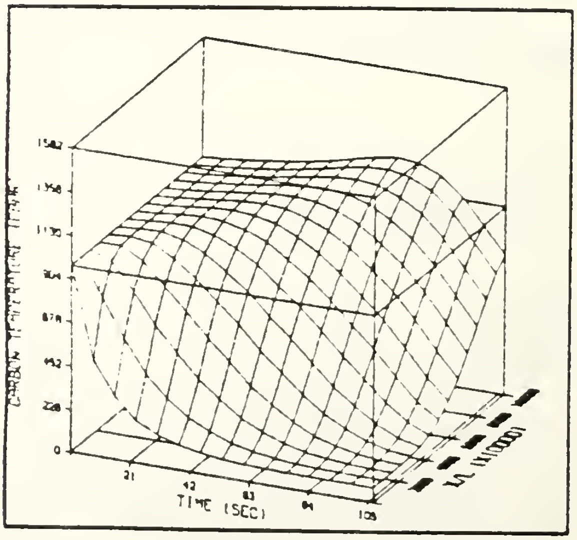


Figure 4.15 Temperature vs X/L and time for permeability = 0.00233 ft^2 initial carbon temperatiure = 970 F.

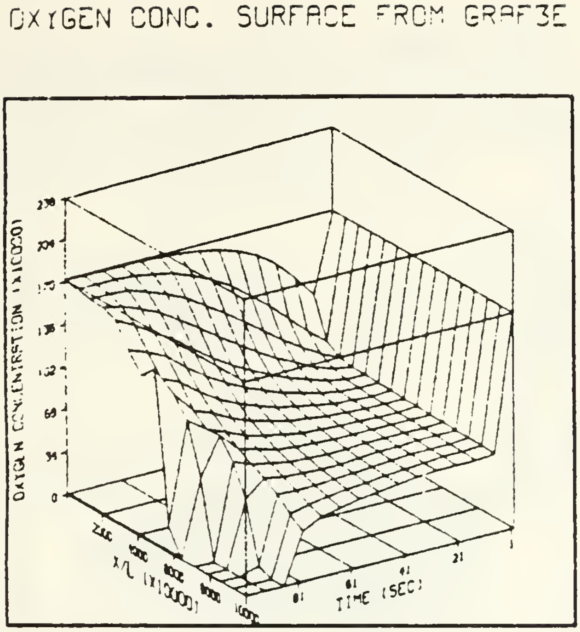


Figure 4.16 Oxygen concentration vs X/L and time for permeability = 0.00233 ft^2 initial carbon temperatiure = 980 F.

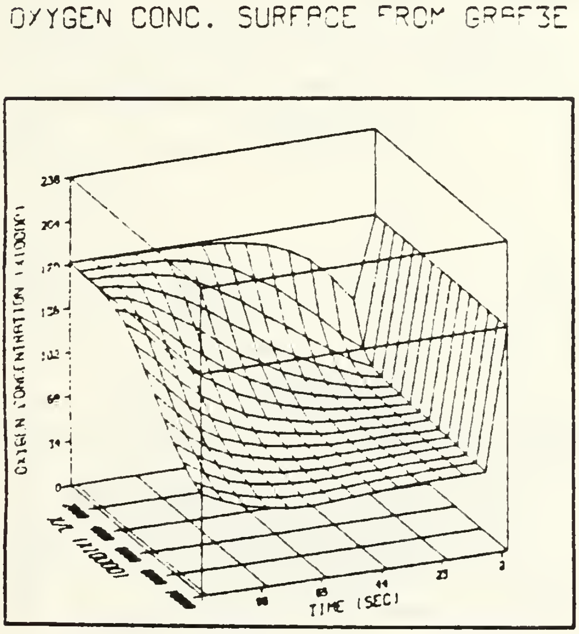


Figure 4.17 Oxygen comcentration vs X/L and time for permeability = 0.00233 ft^2 initial carbon temperatiure = 970 F.

REACTION RATE SURFACE FROM GRAF3E

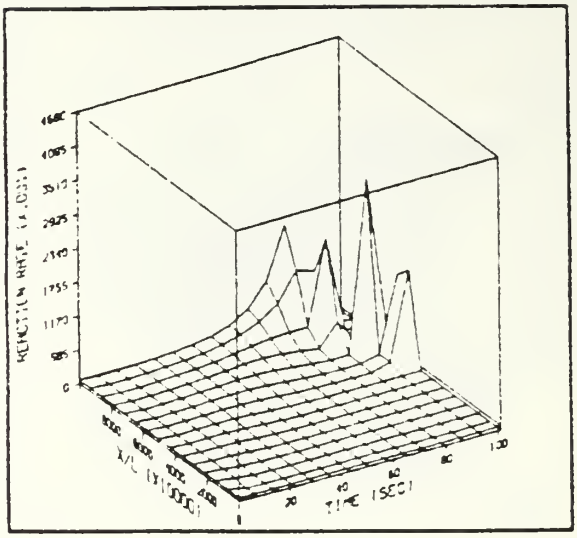


Figure 4.18 Reaction rate vs X/L and time for permeability = 0.00233 ft^2 initial carbon temperatiure = 980 F.

REACTION RATE SURFACE FROM GRAF3E

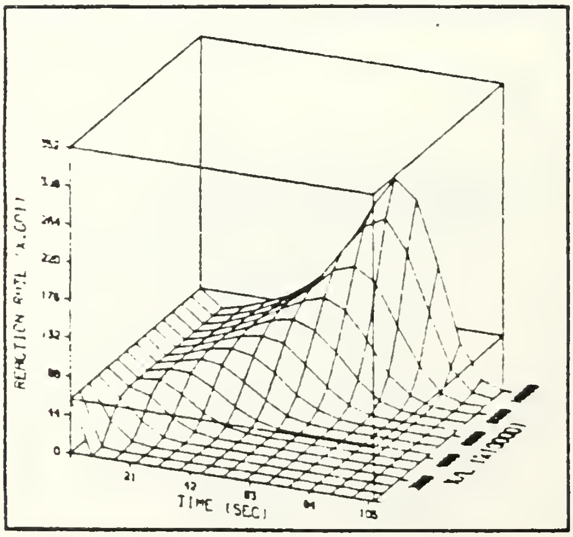


Figure 4.19 Reaction rate vs X/L and time for permeability = 0.00233 ft^2 initial carbon temperatiure = 970 F.

4. CASE IV-4 Permeability = 0.00933 ft^2 (d=D=0.0200 in)

The combustion and extinction temperatures for this case , with initial permeability equal to 0.00933 ft^2 , are:

for combustion T_c = 1180 0.F
for extinction T_e = 1170 0.F

for this case , it was not possible to obtain the graphical surfaces due to limitations of the graphical program .

D. SUMMARY

Here , some observations about the effects of permeability on combustion can be understood by looking at all the results at one time . Table XIII contains the results of all cases .

The Table lists the temperatures for extinction and combustion ,the permeability (m) , the dimension of the unit cell (d=D) and time t* . The t* time is the time at which the oxygen concentration at a point reaches zero first . That point of the porous medium that first reaches zero oxygen concentration in all these cases is the the position point X/L = 1 .

1. Power Relation

The pair of values (permeability , combustion temperature) for each case was plotted on a cartesian graph. An observation of this curve shows that the combustion temperature increases with increasing permeability. Figure 4.20 shows that the combustion temperature increases monotonically and approaches an assindoticptate as permeability increases . The plot of these same points on a log-log graph , Figures 4.21 , shows that its form is not quite a straight line .

It is observed that the relation between combustion temperature (T_c) and permeability (m) yields the approximate power relation (equation 4.9) :

TABLE XIII

RESULTS FOR PERMEABILITY

			temperature (o F)		
	m (ft^2)	(d=D) (in)	Tc	Te	t* (s)
CASE IV-1	0.00015	0.0025	760	750	420
CASE IV-2	0.00058	0.0050	850	840	220
CASE IV-3	0.00233	0.0100	980	970	83
CASE IV-4	0.00933	0.0200	1180	1170	23

$$T_c = 1880\ m^{0.105} \qquad (4.9)$$

A comparation of the values of the combustion temperature obtained by the program and by the power relation is presented in Table XIV . This Table shows that the difference between these results fail between 1.2 to 3.2 percent . This result shows that the above power relation is a good approximation to estimate the temperature which will start combustion for a given permeability .

2. Combustion Speed

In this section , the question of how permeability affects the time it takes for combustion to begin is addressed . We meassure the rapidilly of the combustion process by the t^* time previously defined . Recall that t^* is the time at which the oxygen first reaches zero at some point in the porous medium . In all cases the position $X/L = 1$ is the first point to achieve zero oxygen concentration . The plots of permeability (m) versus t^* , Figures 4.22 and 4.23 , show that t^* decays exponentially with increasing permeability and approaches an assymptotic value of $t^* = 0$ as m goes to infinity .

A very interesting observation is obtained from the results of Table XIII . It is noted that the m_{i+1}/m_i (for $i = 1,2,3$) remains pratically constant (3.84 , 4.01 , 4.00) while the t^*_{i+1}/t^*_i ratio takes on the variable values $1/(i+1)$ (1/1.91 , 1/2.65 , 1/3.56) .

An attempt was made to obtain an additional run with the permeability equal to 0.03733 ft^2 , however the combustion activity was too rapid to achieve meaningful results . Combustion was achieved so rapidly that the gradient were too large for the program to handle .

The permeability is a parameter that has great influence on the combustion process for porous medium .

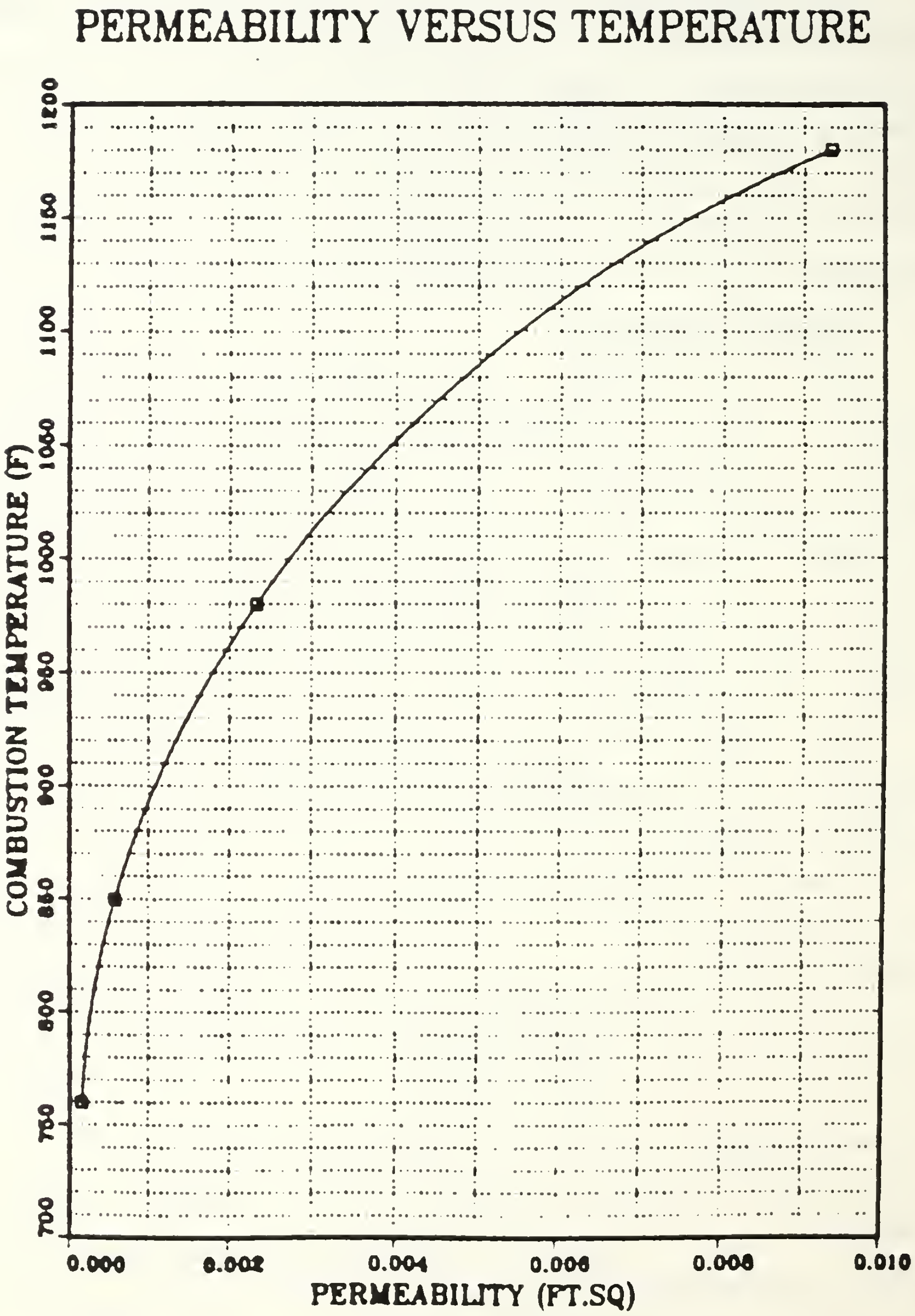


Figure 4.20 Permeability versus combustion temperature retangular plot.

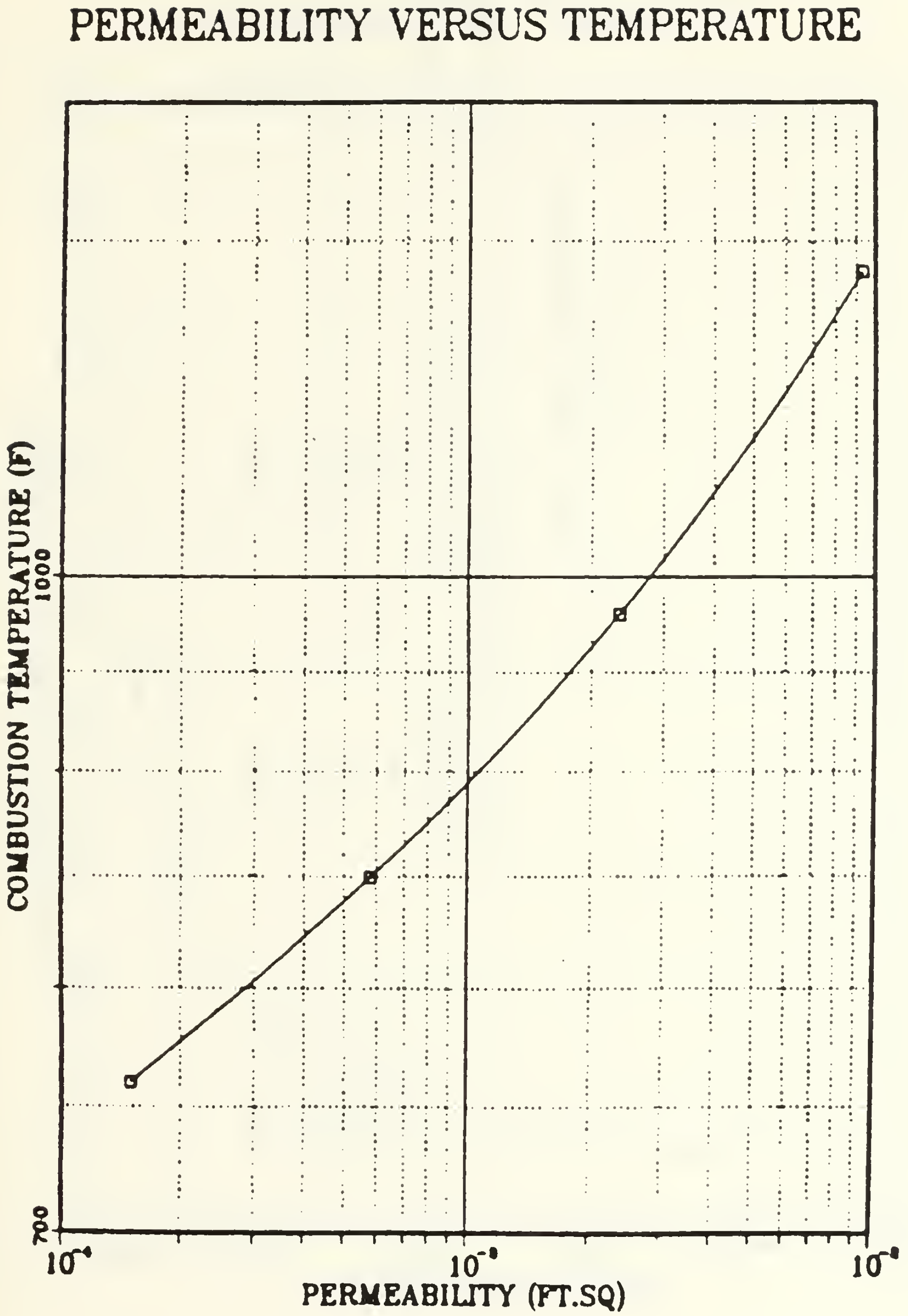


Figure 4.21 Permeability versus combustion temperature log log plot.

TABLE XIV

POWER RELATION RESULTS

	combustion temperature (o.F)		difference
	program's	power relation	in percent
CASE IV - 1	760	745.8	1.9
CASE IV - 2	850	859.6	1.1
CASE IV - 3	980	994.8	1.5
CASE IV - 4	1180	1150.8	2.5

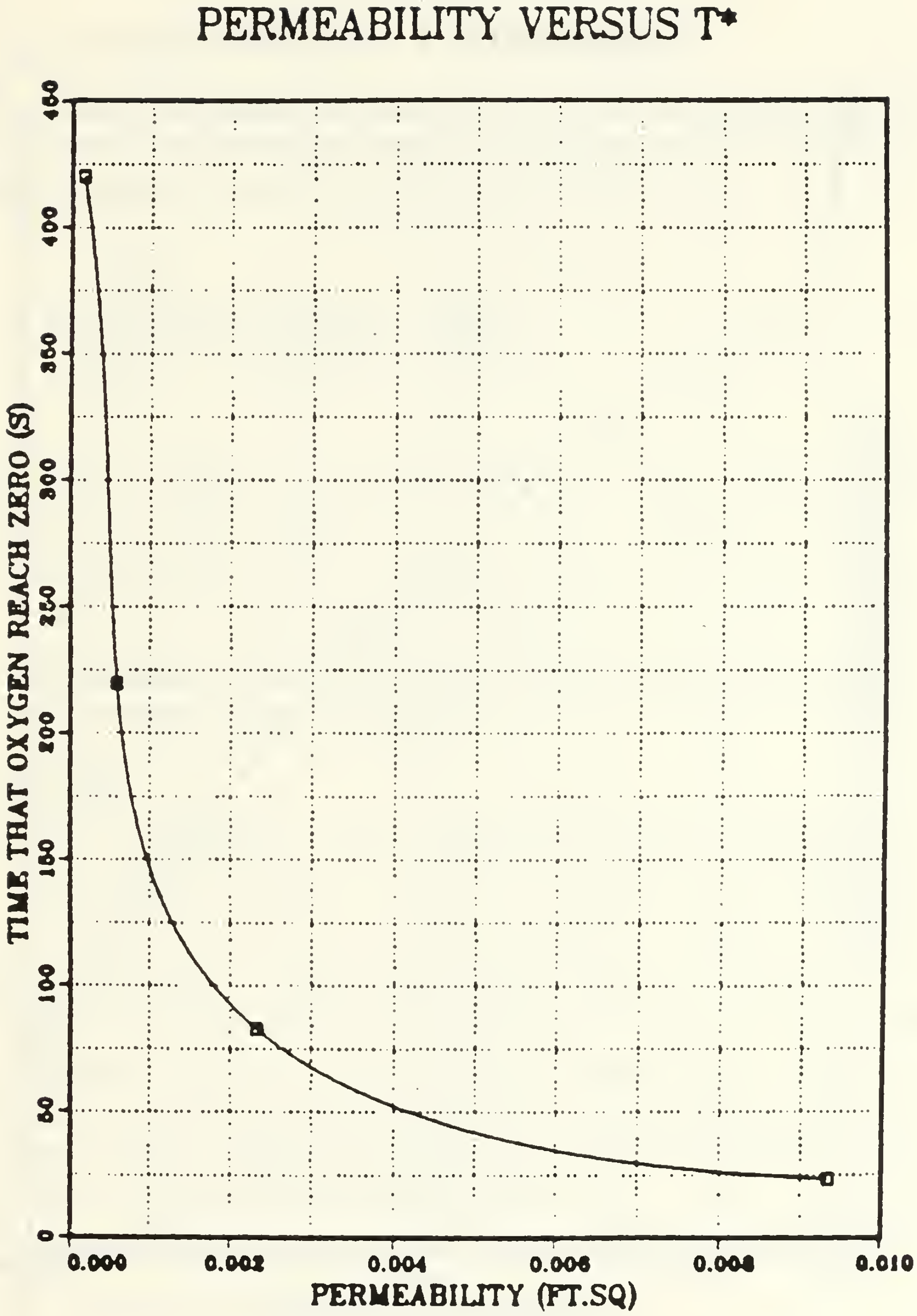


Figure 4.22 Permeability versus t*
Retangular plot.

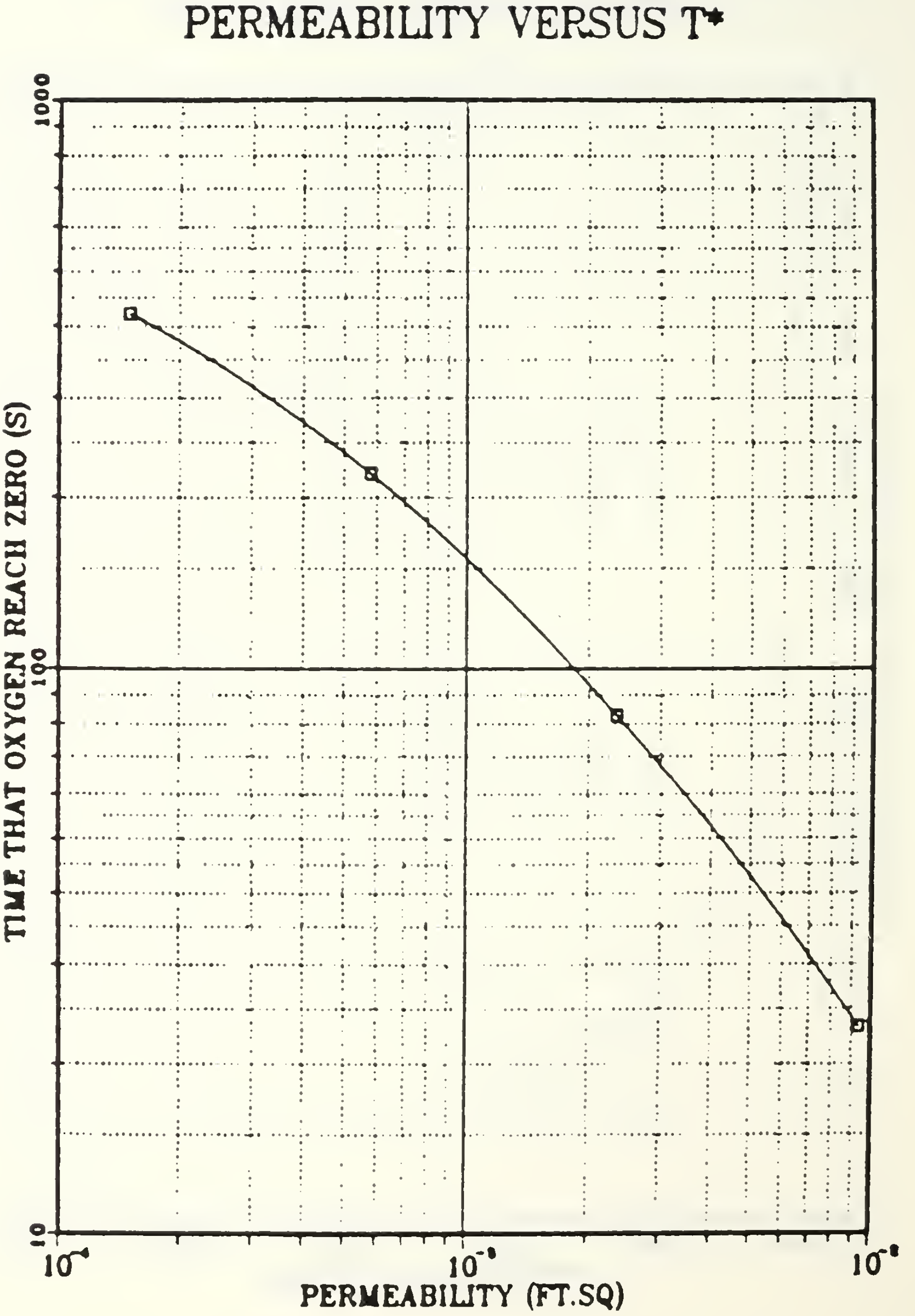


Figure 4.23 Permeability versus t*
Log-log plot.

V. REACTION ORDER

A. INTRODUCTION

The expression for reaction rate for carbon reacting in air used in the program was the expression resulting from the experimental data of Parker and Hotel .

$$R_c = A \frac{P_{O_2}^n}{\sqrt{T_c}} \exp\left(\frac{-E}{\mathcal{R} T_c}\right) \quad \frac{gr\text{-}c}{cm^2 s} \tag{5.1}$$

Reaction order is the exponent of the partial pressure of oxygen in the expression of the reaction rate . The program permits the user to select any value for this parameter . In all of the previous chapters , a value of n equal to 0.5 was used . In this chapter we investigate the effect of n on the combustion process .

B. PROCEDURE

In this section , all parameters are fixed to their basic values and only the reaction order is changed in each case .

The program was run , for each value of reaction order , with different value of the uniform initial carbon temperature until we obtained the minimum temperature which results in combustion . This temperature is the combustion temperature (T_c) . The maximum temperature that results in extinction is the extinction temperature (T_e). they differ by an infinitesimal δ ($T_c = T_e + \delta$) . The magnitude of δ was chosen equal to 10 F for this study .

In order to study the influence of the reaction order on the combustion process , four different values of this parameter were chosen . These cases are :

CASE V-1	Reaction Order = 0.25
CASE V-2	Reaction Order = 0.50
CASE V-3	Reaction Order = 0.75
CASE V-4	Reaction Order = 1.00

The fixed parameters used in all cases are :

Ambient temperature = 80 F
Ambient pressure = 2117 lb/ft.sq
Tortuosty = 1.400
Filamento diameter = 0.0004167 ft
Thickness of matrix laminette = 0.0004167 ft
Thickness of porous medium = 0.02083 ft
Gas constant for air = 53.34 lbf ft/lbm R
Conductivity of filament = 86 BTU/lbm H.F.
Specific heat of filament = 0.703 lbm/Cf
Emissivity of filament = 0.90
Shape factor for internal HFxFER =1.00
Characteristc length of medium = 1 inchess
Heat of reaction = 14090 BTU/Cf
Stochiometric ratio (fuel/air) = 0.375
Reaction coefficient = 2065000 lbm/Cf H
Activetion energy coefficient = 28840 deg R
Pressure differential across thickness = 50 lb/ft.sq
Initial uniform oxygen concentration = 0.172 lbm/ft^3

C. RESULTS

For each cases the results were obtained in both numerical and graphical form . These results show the variation of some parameters during the combustion and extinction processes . The results obtained for each value of reaction order are presented below

1. CASE V-1 Reaction Order = 0.25

With this value of reaction order , the combustion and extinction processes define the following characteristic temperatures :

for combustion T_c = 980 o.F
for extinction T_e = 970 o.F

The analysis of the numerical output of the program shows that some parameters varied during the combustion and extinction processes . The limits of these parameters show the character of the particular kind of process which occured .

The graphical results show three surfaces that represent the evolution of the carbon temperature , oxygen concentretion and reaction rate at each position during the transient history . These graphical surfaces are shown in Figures 5.1 to 5.6 .

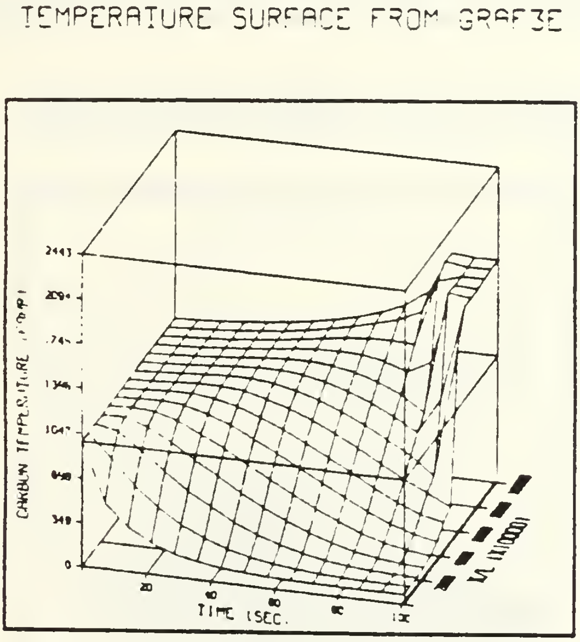
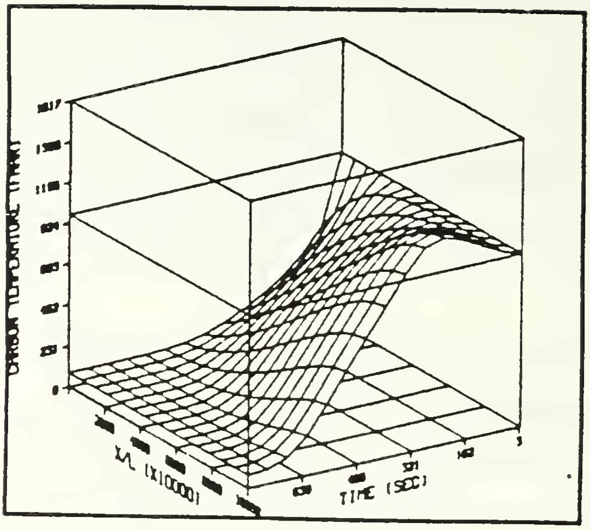
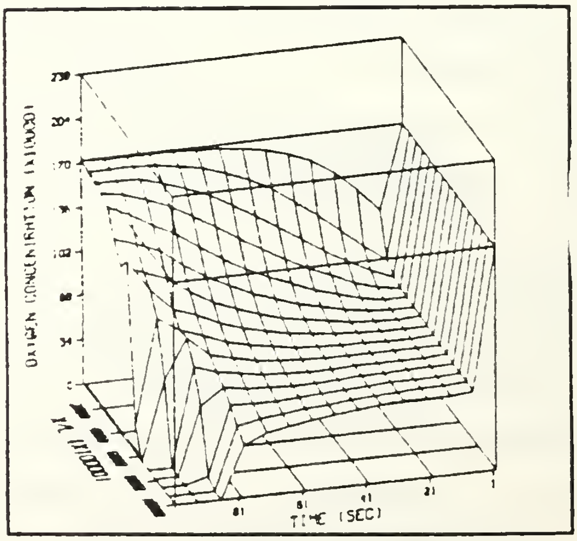


Figure 5.1 Temperature vs X/L and time
for reaction order = 0.25
Initial carbon temperature = 980 F.



TEMPERATURE SURFACE FROM GRAF3E

Figure 5.2   Temperature vs X/L and time
for reaction order = 0.25
Initial carbon temperature = 970 F.



OXYGEN CONC. SURFACE FROM GRAF3E

Figure 5.3   Oxygen concentration vs X/L and time
for reaction order = 0.25
Initial carbon temperature = 980 F.

OXYGEN CONC. SURFACE FROM GRAF3E

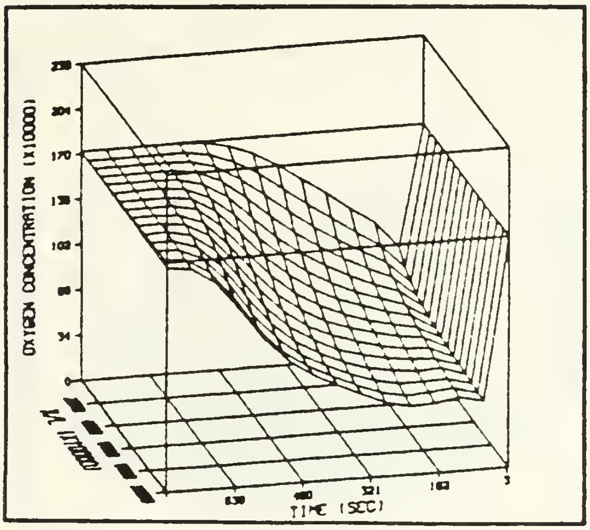


Figure 5.4 Oxygen concentration vs X/L and time for reaction order = 0.25
Initial carbon temperature = 970 F.

REACTION RATE SURFACE FROM GRAF3E

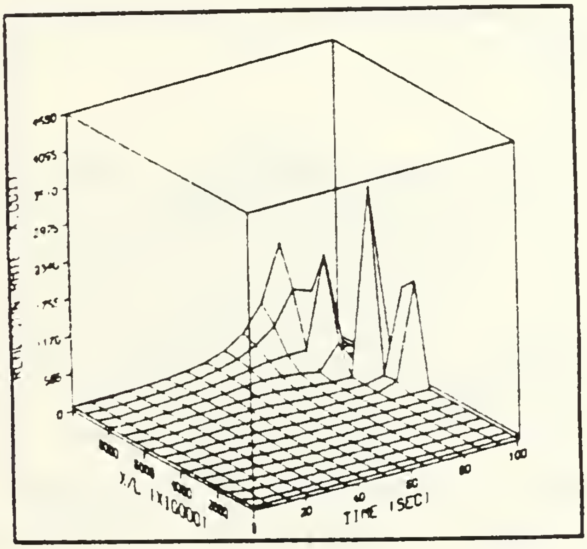


Figure 5.5 Reaction rate vs X/L and time for reaction order = 0.25
Initial carbon temperature = 980 F.

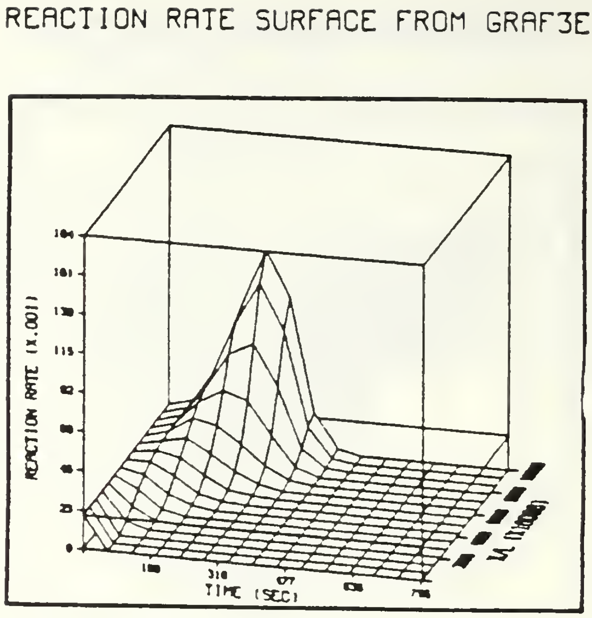


Figure 5.6 Reaction rate vs X/L and time
for reaction order = 0.25
Initial carbon temperature = 970 F.

2. CASE V-2 Reaction Order = 0.50

For reaction order equal to 0.50 , the initial uniform carbon temperatures that separate the combustion and extinction processes are :

for combustion T_c = 980 F
for extinction T_e = 970 F

The program's numerical output included the values of some parameters that varied during the transient process. The variation of the values characterize the combustion or extinction process. The graphical results are shown in three surfaces: carbon temperature, oxygen concentration and reaction rate versus position (X/L) and time. These graphical surfaces are shown in figures 5.7 to 5.12 .

TEMPERATURE SURFACE FROM GRAF3E

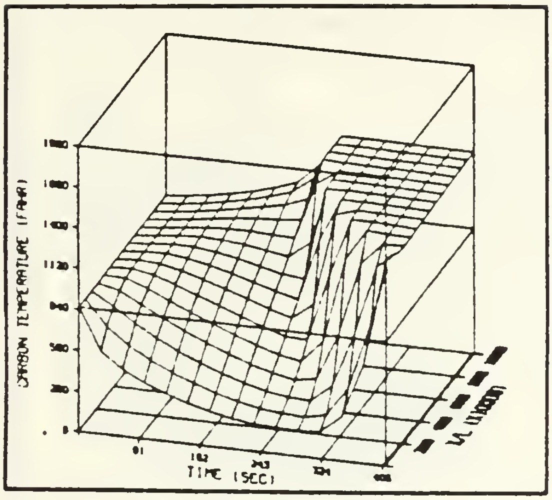


Figure 5.7 Temperature vs X/L and time
for reaction order = 0.50
Initial carbon temperature = 850 F.

TEMPERATURE SURFACE FROM GRAF3E

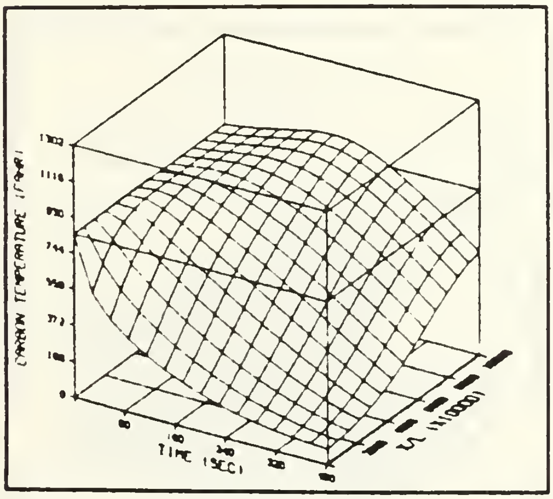


Figure 5.8 Temperature vs X/L and time
for reaction order = 0.50
Initial carbon temperature = 840 F.

OXYGEN CONC. SURFACE FROM GRAF3E

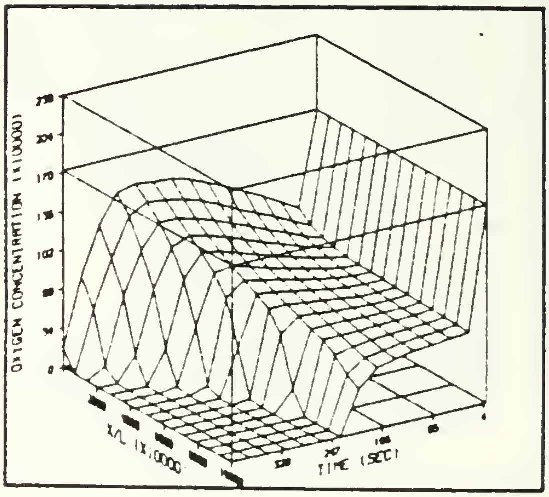


Figure 5.9 Oxygen concentration vs X/L and time
for reaction order = 0.50
Initial carbon temperature = 850 F.

OXYGEN CONC. SURFACE FROM GRAF3E

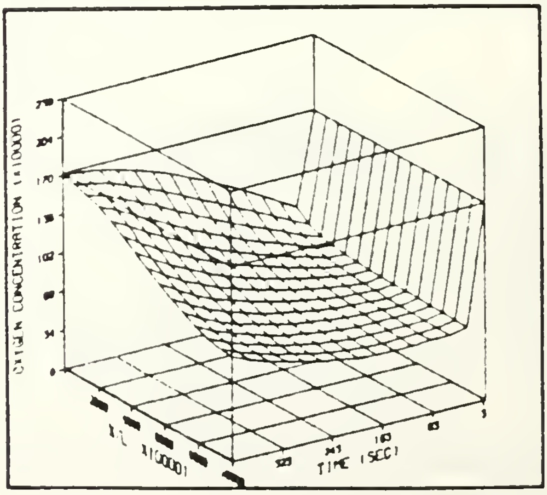


Figure 5.10 Oxygen concentration vs X/L and time
for reaction order = 0.50
Initial carbon temperature = 840 F.

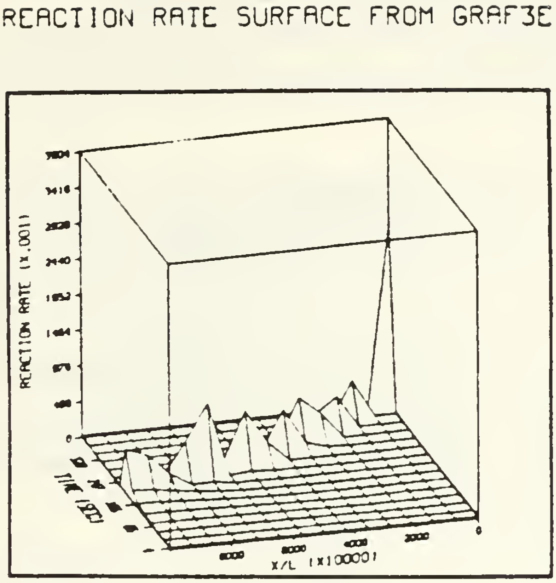


Figure 5.11 Reaction rate vs X/L and time for reaction order = 0.50 Initial carbon temperature = 850 F.

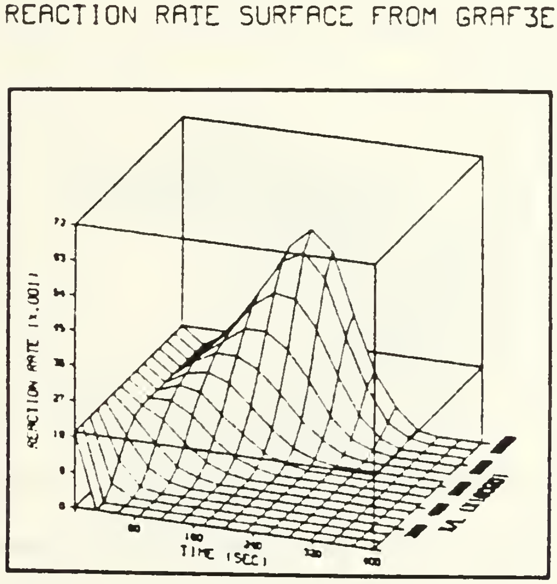


Figure 5.12 Reaction rate vs X/L and time for reaction order = 0.50 Initial carbon temperature = 840 F.

3. CASE V-3 Reaction Order = 0.75

The reaction order was set equal to 0.75 for this case. The combustion and extinction temperatures are:

for combustion Tc = 750 F
for extinction Te = 740 F

A visualization of the development of the carbon temperature, oxygen concentration and reaction rate at each position and time are shown in the graphical surfaces of Figures 5.13 to 5.18 .

TEMPERATURE SURFACE FROM GRAF3E

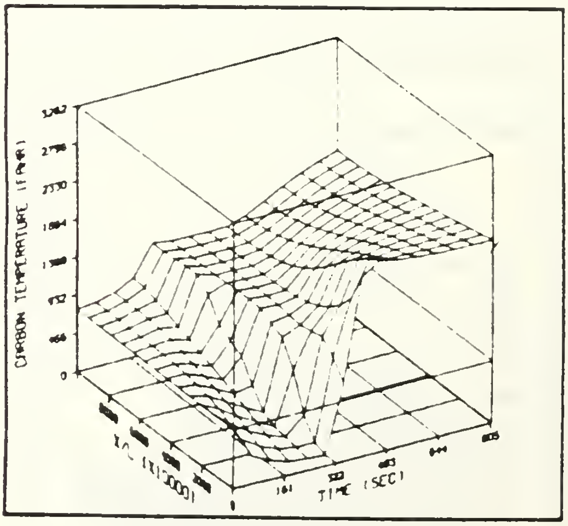


Figure 5.13 Temperature vs X/L and time for reaction order = 0.75 Initial carbon temperature = 750 F.

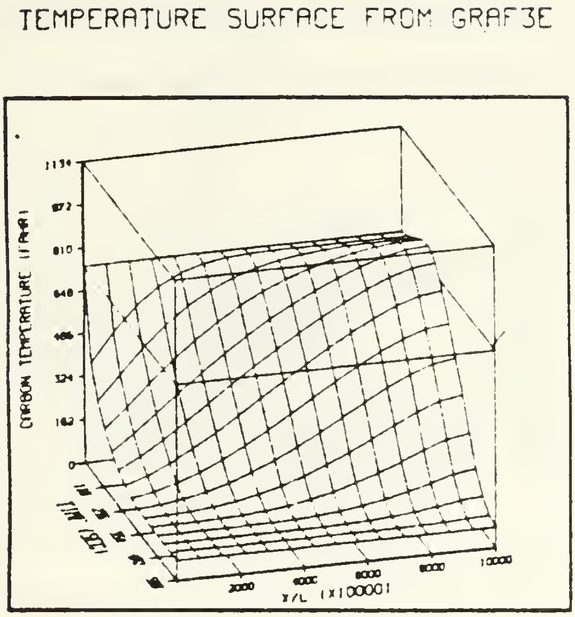


Figure 5.14 Temperature vs X/L and time for reaction order = 0.75 Initial carbon temperature = 740 F.

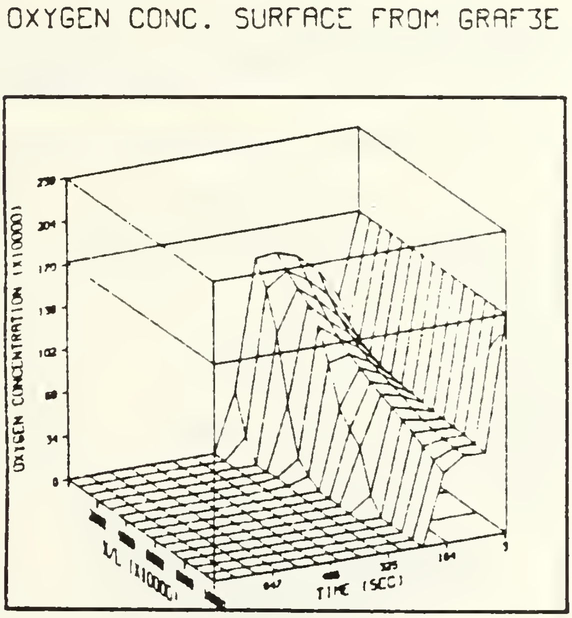


Figure 5.15 Oxygen concentration vs X/L and time for reaction order = 0.75 Initial carbon temperature = 750 F.

OXYGEN CONC. SURFACE FROM GRAF3E

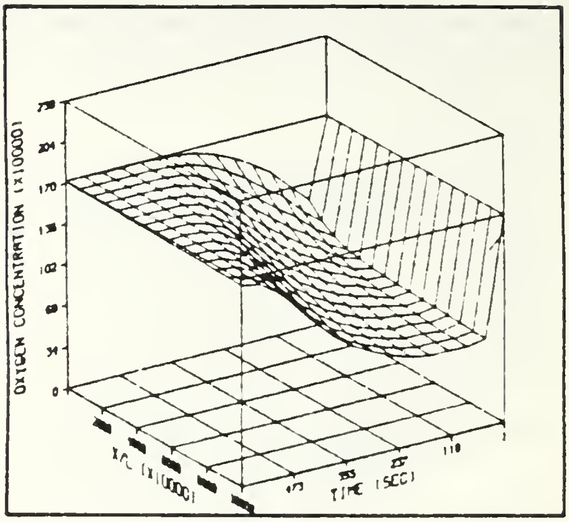


Figure 5.16 Oxygen concentration vs X/L and time
for reaction order = 0.75
Initial carbon temperature = 740 F.

REACTION RATE SURFACE FROM GRAF3E

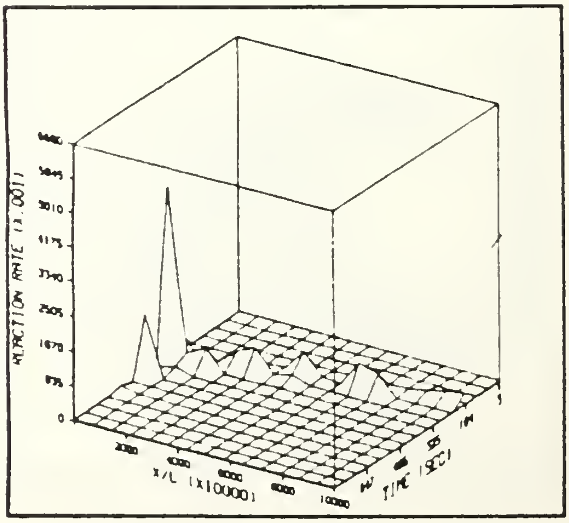


Figure 5.17 Reaction rate vs X/L and time
for reaction order = 0.75
Initial carbon temperature = 750 F.

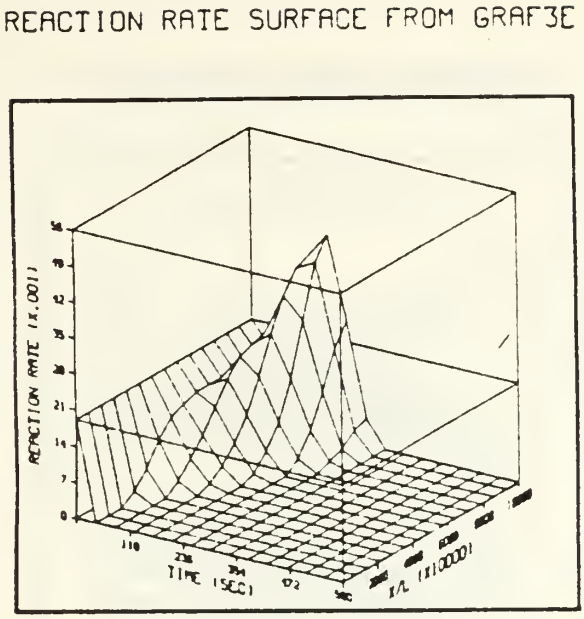

REACTION RATE SURFACE FROM GRAF3E

Figure 5.18 Reaction rate vs X/L and time
for reaction order = 0.75
Initial carbon temperature = 740 F.

4. CASE V-4 Reaction Order = 1.00

For this case, the temperature of the combustion and extinction processes are:

for combustion T_c = 670 F
for extinction T_e = 660 F

The Figures 5.19 to 5.24 show the behavior of the carbon temperature, oxygen concentration and reaction at each position and time.

D. SUMMARY

1. Power Relation

For each case, a pair of values (reaction order, combustion temperature) was obtained.The points were plotted in cartesian coordinates in Figure 5.25 . A log-log plot is shown in Figure 5.26 , and a semi log plot is shown in Figure 5.27 . It is observed that the relation between

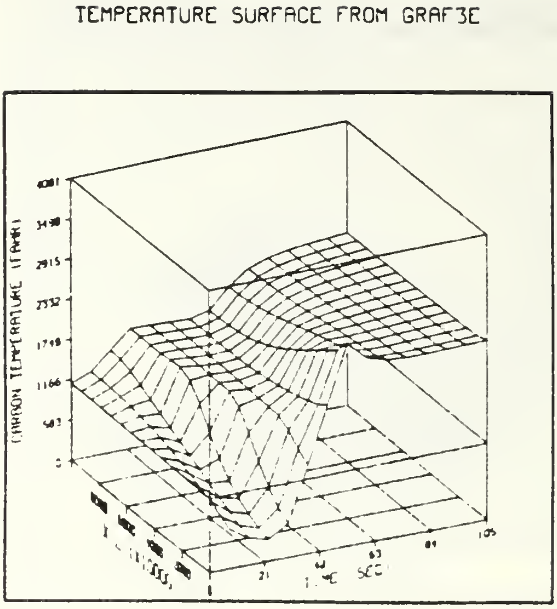


Figure 5.19 Temperature vs X/L and time
for reaction order = 1.00
Initial carbon temperature = 670 F.

reaction order (n) and combustion temperature (T_c) of figure 5.27 yields the approximate power relation (equation 5.2) .

Table 5.25 shows a resume of each case, combustion temperature, extinction temperature and the value of the combustion temperature obtained from Equation 5.2 and the percentage error . An observation of these results leads to the conclusion that this power relation is a good estimation for combustion temperature.

TEMPERATURE SURFACE FROM GRAF3E

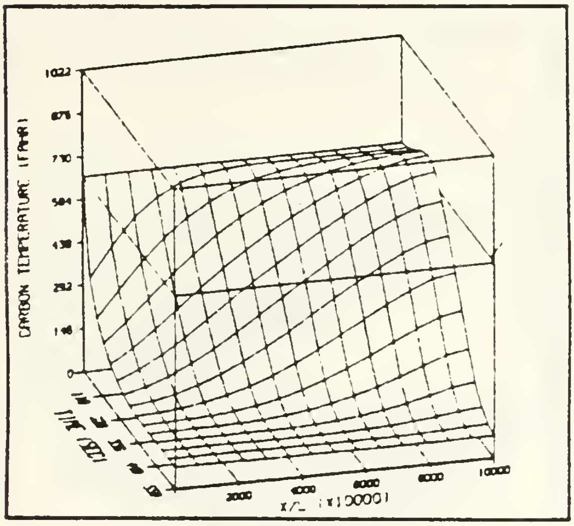


Figure 5.20 Temperature vs X/L and time
for reaction order = 1.00
Initial carbon temperature = 660 F.

OXYGEN CONC. SURFACE FROM GRAF3E

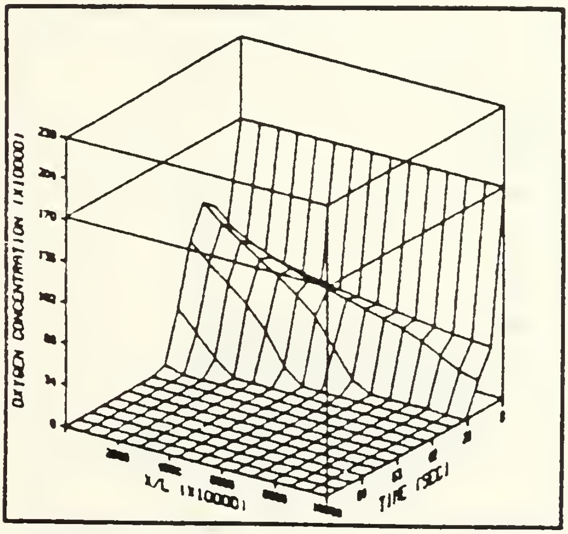


Figure 5.21 Oxygen concentration vs X/L and time
for reaction order = 1.00
Initial carbon temperature = 670 F.

OXYGEN CONC. SURFACE FROM GRAF3E

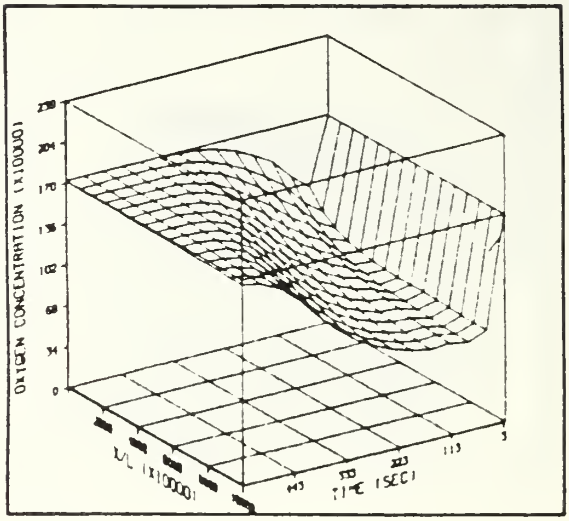


Figure 5.22 Oxygen concentration vs X/L and time for reaction order = 1.00 Initial carbon temperature = 660 F.

REACTION RATE SURFACE FROM GRAF3E

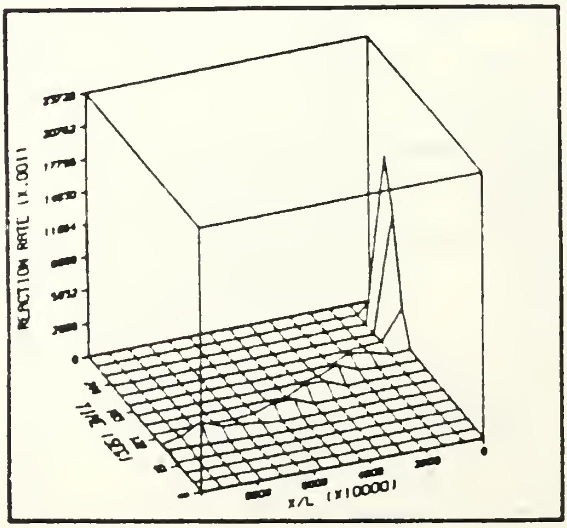


Figure 5.23 Reaction rate vs X/L and time for reaction rate= 1.00 Initial carbon temperature = 670 F.

REACTION RATE SURFACE FROM GRAF3E

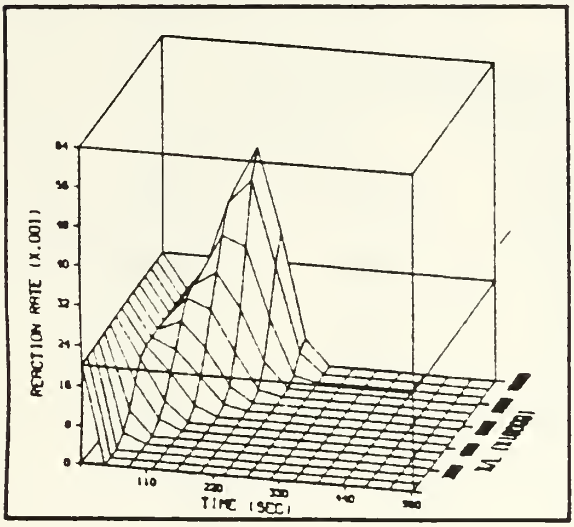


Figure 5.24 Reaction rate vs X/L and time
for reaction order = 1.00
Initial carbon temperature = 660 F.

$$T_c = 10^{(3.05-0.22n)} \quad (\ \mathrm{F}) \tag{5.2}$$

TABLE XV

COMBUSTION AND EXTINCTION TEMPERATURE FOR REACTION ORDER CASES

	temperatures ($_o$F)			
	extinction	combustion		% error
reaction order	program output	program output	power relation	
0.25	970	980	980	0.0
0.50	840	850	863	1.6
0.75	740	750	760	1.4
1.00	670	670	670	0.0

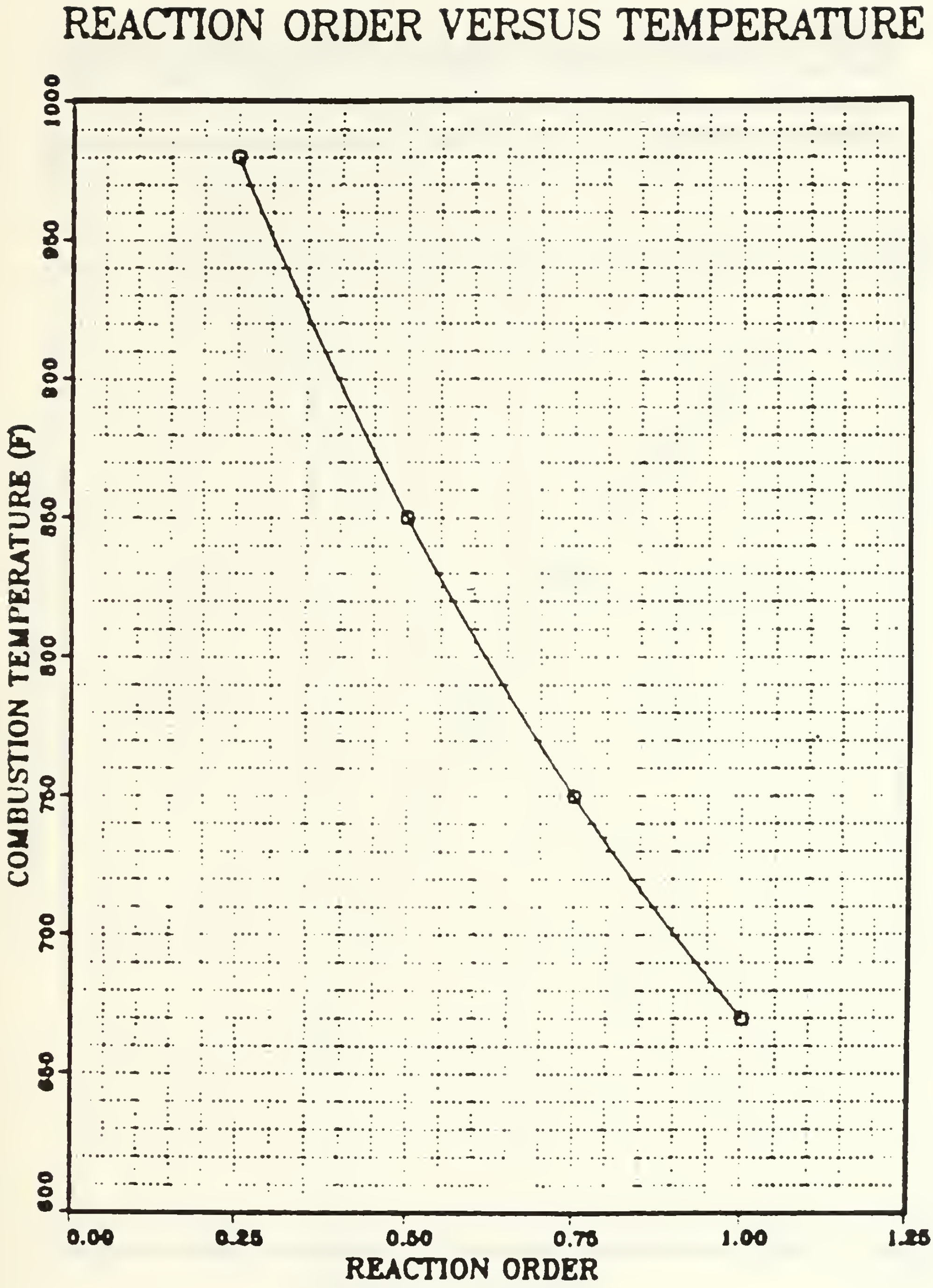


Figure 5.25 Reaction order versus temperature Retangular plot.

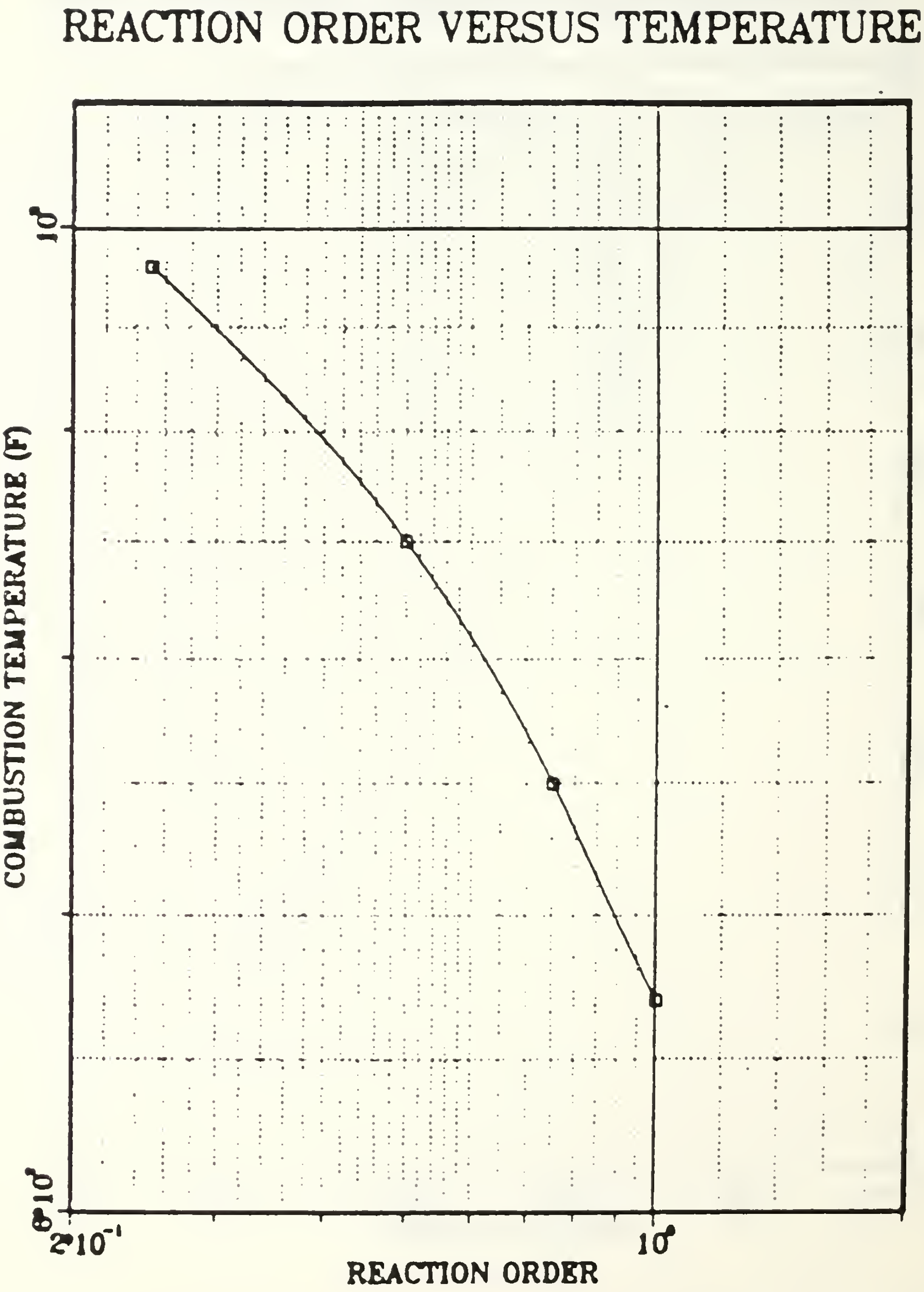


Figure 5.26 Reaction order versus temperature Log-log plot.

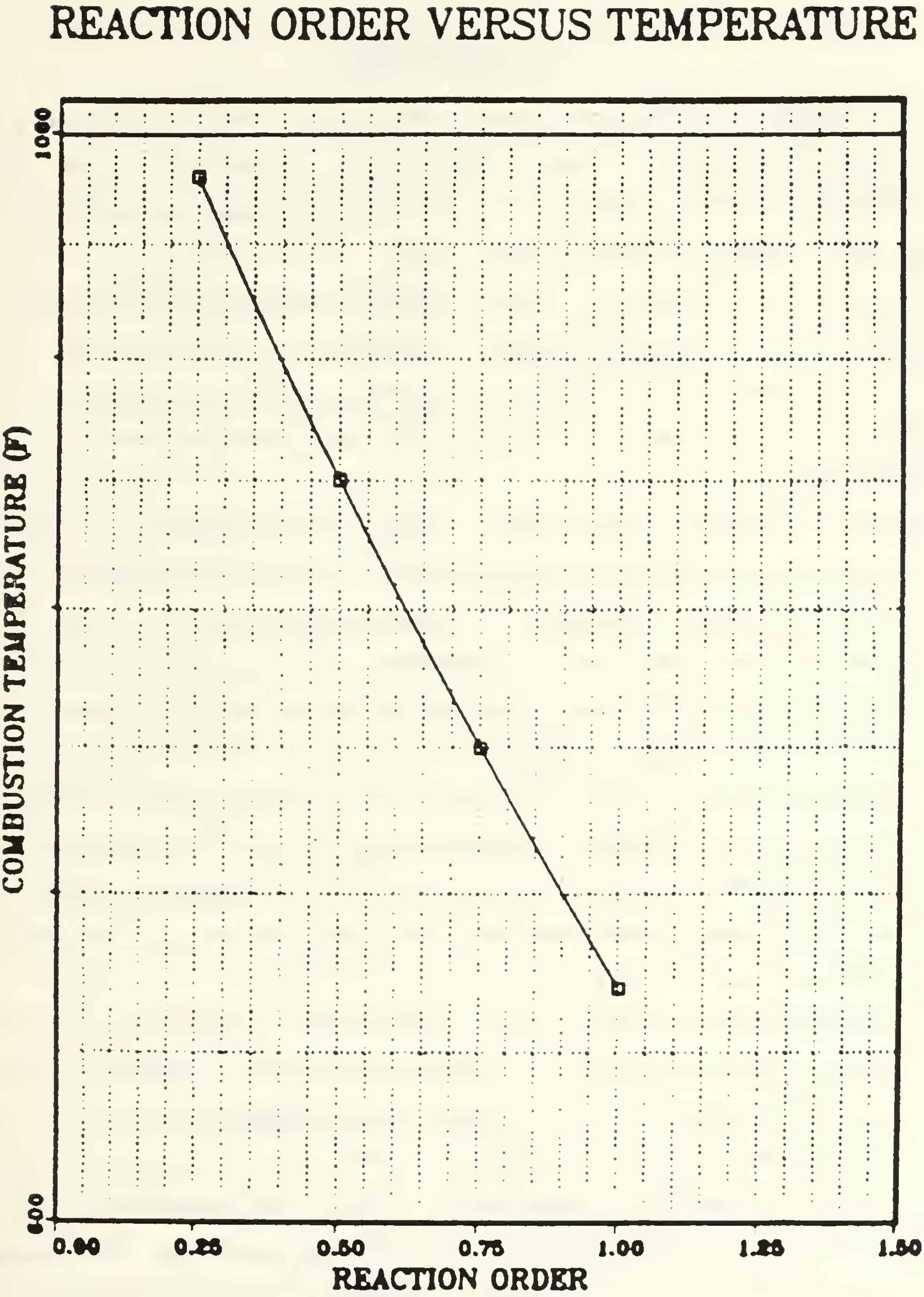


Figure 5.27 Reaction order versus temperature
Semi log plot.

VI. CONCLUSIONS

In each of the previous chapters, the effects of a single parameter on the combustion behavior of a porous medium was investigated. In Chapter 2, we considered the effect of heat flux (SQ) and its duration (TQ) on combustion. In Chapter 3, the effect of medium thickness (L) on behavior was investigated. Chapter 4 was a study of the effect of permeability (m) on system behavior; and finally in Chapter 5, the effect of reaction order (n) was investigated.

The major conclusions from these investigations are:

- The relation between SQ and TQ is not linear , a power relation gives rasonable approximation.
- During the combustion process, for the SQ cases, initially there is a large temperature gradient across the medium with $T (X/L = 0.) >> T (X/L = 1.)$. With passing time, this gradient decreases until there is a uniform combustion temperature over the entire medium. When this occurs, there is no oxygen within the medium, and the medium is continuosly consumed by combustion.
- The relation between thickness and combustion temperature is not linear . Increasing the thickness results in decreasing of combustion temperature. If the thickness increased with a constant rate c ($L_{i+1}/l_i = c$) the time that marks the start of combustion is not constant , it increases with increasing thickness (i.e. $t^*_{i+1}/t^*_i = b(L)$) where b depends upon the thickness .
- The relation between permeability and minimum combustion temperature is not linear.
- An increase of the permeability shows that the combustion temperature increases to an asymptotic limit.

- Permeability has a significant influence on the speed of the combustion process. When the permeability is increased, the time that marks the start of the combustion process decreases. For large values of permeability, the combustion may occur in a fraction of a second.
- If the permeability is increased with a constant rate c($m_{i+1} = c\ m_i$) , the time that measures the start of combustion decreases .
- The relation between reaction order (n) and combustion temperature (Tc) is not linear.
- An observation of the graphical surfaces, for all cases of this investigation , shows a similar form for all combustion and extinction cases. For all combustion cases, it was noted that the oxygen within the porous medium being consumed with passing time. The first point at which the oxygen is depleted is always X/L = 1. With passing time the point with smaller X/L reach zero oxygen, until all points have zero oxygen. At this time the only oxygen is at the interface of the porous medium and the ambient environment. At this time the combustion process becomes a surface recession phenomena. At the same time the oxygen is being depleted the temperature is increasing. Eventually when all the interior oxygen has been consumed, there is a temperature gradient across the medium with $T_c(X/L=0) > T_c(X/L=1)$.

This thesis concludes with two recomendations . First , it is recommended that additional parameter studies he conducted . For example , it would be useful to determine the effects of pressure differential , conductivity , and other thermophysical properties on combustion . Another recommendation is to attempt to obtain a relation between combustion temperature and several parameters .

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2. Semenov, N. N., Chemical Kinetics and Chain Reaction, Clarendon Press, Oxford, 1935.

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